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Spatio-Temporal Patterns of Geomorphic Adjustment in Channelized Tributary Streams of the Lower Hatchie River Basin, West Tennessee

Mary A. Boulton
University of Tennessee - Knoxville

To the Graduate Council:

I am submitting herewith a dissertation written by Mary A. Boulton entitled "Spatio-Temporal Patterns of Geomorphic Adjustment in Channelized Tributary Streams of the Lower Hatchie River Basin, West Tennessee." I have examined the final electronic copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Geography.

Carol P. Harden, Major Professor

We have read this dissertation and recommend its acceptance:

Accepted for the Council:

<u>Carolyn R. Hodges</u>

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

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Vice Chancellor and Dean of Graduate Studies

SPATIO-TEMPORAL PATTERNS OF GEOMORPHIC ADJUSTMENT IN CHANNELIZED TRIBUTARY STREAMS OF THE LOWER HATCHIE RIVER BASIN, WEST TENNESSEE

A Dissertation
Presented for the
Doctor of Philosophy
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Mary Alice Davis Boulton
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DEDICATION

This dissertation is dedicated to Tom and Carol Byrne for giving me encouragement and support when needed most.

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ABSTRACT

The processes involved in fluvial geomorphic adjustment to human-induced change are not well understood, despite an increasing and global prevalence of human disturbance to rivers. This doctoral dissertation research examines spatial and temporal patterns of geomorphic adjustment processes in three tributary streams of the Lower Hatchie River Basin, in west Tennessee, which are adjusting to historic land clearance and channelization. This dissertation examines (1) the types and spatial pattern of geomorphic adjustment processes in a total of 34 tributary reaches located in Richland, Jeffers, and Dry Creeks, (2) the applicability of an existing model of geomorphic adjustment for use in tributary streams with multiple episodes of disturbance, (3) sediment dynamics at the reach scale, including floodplain and channel re–coupling, and (4) the connections between reach-scale processes of sediment dynamics and system-wide geomorphic response.

Results from this dissertation research suggest that after an initial period of downcutting, channel widening involving bank failure and bank undercutting are the dominant adjustment mechanisms, and create asymmetrically–shaped channels. Bank failures in the study tributaries are common and are produced by progressive bank undercutting related to redirection of flow towards banks by well–developed bars and berms deposited in the channel. The lifetime of channel bars and berms appears to be long, enduring beyond seven months of monitoring. The common occurrence of asymmetric channels

and well–developed bar and berm deposits throughout each of the three study tributaries lends field–based support for the operation of bar-bend processes of lateral migration. These results highlight the important role of lateral adjustment processes post–channelization and sediment storage in determining the location of geomorphic processes and potentially initiating system–wide lateral migration. Applicability of the Channel Evolution Model may be limited in tributary streams with multiple periods and/or locations of channelization because it focuses on the area of maximum disturbance, and it lacks explicit incorporation of lateral migration processes and sediment dynamics.

Field-based sediment monitoring and simulation of sediment connectivity using channel morphometrics and Multi-Response Permutation Procedure suggest that sediment dynamics remain in a state of adjustment, lacking suitable long–term storage of sediment due to floodplain/channel de–coupling and irregular sediment transport. Analysis of a core taken from one re–coupled floodplain in Richland Creek suggests that re–coupling is possible but, in this instance, required more than 50 years to occur. This indicates that sediment will continue to be stored in the channel well into the future, potentially prolonging channel widening and lateral migration processes. Finally, results from this research suggest that spatial and temporal patterns of geomorphic adjustment depend upon reach–scale processes of sediment dynamics and flow deflection. The dominance of reach–scale dynamics in the tributaries calls into question the applicability of numerical models developed on a watershed-based approach and demonstrates the need to understand reach–scale controls of system–wide response in fluvial systems.

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CHAPTER 1

Introduction

Human modifications of river systems, involving land clearance, agriculture, industry, channelization, recreation, and urbanization, have reduced drinking water quality and impaired aquatic habitats worldwide. In recent decades, people, including natural resource managers and, to some extent, the public at large, have altered their perception of rivers as natural systems requiring control and manipulation and, instead, begun to view rivers as natural systems in need of restoration and conservation (Bockelmann *et al.*, 2004). This change in the perception of rivers, coupled with the desire to regain ecosystem functions and improve environmental aesthetics in disturbed rivers (Montgomery, 2001), has increased interest in river restoration. As a result, river restoration and its practitioners have gained considerable attention from conservationists, non-profit organizations, government resource management agencies, and to a limited extent, the public at large, as indicated by a recent Time Magazine interview with Dr. Dave Rosgen, a hydrology consultant (Time Magazine, April 2004). The idea and practice of river restoration embodies and involves a wide array of ideals and methods. It involves management practices designed "to rehabilitate, enhance, recover, or create" river environments (Brookes, 1999), and usually involves structural and functional changes made to river channels, riparian corridors, and/or watershed land use to support some established goal or ideal, including, but not limited to, aquatic habitat, drinking water quality, river aesthetics, and recreational demands.

Because of variable river restoration ideals and practices, which vary depending on the target of concern, a better understanding of fluvial geomorphic adjustment processes in disturbed watersheds is needed more than ever. Restoration projects are developing rather quickly. However, the full spectrum of geomorphic adjustment processes, specifically spatial and temporal patterns of change, has yet to be fully identified and understood to ensure that restoration efforts are effective and do not undermine natural geomorphic adjustment processes.

In addition to the applied need for more research into geomorphic adjustment to human-induced change, many gaps in the conceptual knowledge exist concerning fluvial geomorphic adjustment to human-induced change. Many questions remain regarding the rates of geomorphic and hydrologic change, the propagation of change within the fluvial system, the timescales required for system recovery, what constitutes recovery (new equilibrium conditions or a return to pre-disturbance conditions?), the interconnections between the different components of the system (specifically, the temporal and spatial scales at which the connections operate), and the coupling of channel and extra-channel components of fluvial systems, such as hillslopes and channels.

Fluvial response to disturbance is complex and not entirely understood. Reasons for this complexity relate to spatial and temporal variability of processes inherent in fluvial systems. A need exists for research into fluvial adjustment and recovery processes because long-term trends and system-wide responses are not well understood.

Research Objectives

In this dissertation, I examine geomorphic adjustment processes occurring in three tributary streams located in the Lower Hatchie River Basin of west Tennessee. The study tributaries have a disturbance history that includes deforestation for agricultural pursuits and channelization, in more recent times.

This dissertation seeks to explain spatial and temporal patterns of geomorphic adjustment processes related to land clearance and channelization by:

1) identifying the connections between reach-scale processes and system-wide responses, and;

2) investigating the role of sediment dynamics in determining the timing and location of geomorphic adjustment processes.

Organization of the Dissertation

This dissertation has six chapters. The remainder of Chapter 1 provides background information about the Lower Hatchie River Basin, including a geomorphic characterization, disturbance history, and a description of soils and climate. Chapter 2 outlines the context of the dissertation research by reviewing literature that details the current understanding of how fluvial systems function and how fluvial systems respond to human-induced disturbances. I wrote Chapters 3, 4, and 5 as individual manuscripts in preparation for submission to professional journals. Each of these chapters summarizes research methods, results, and interpretation/discussion of results for different specific research questions addressed by the dissertation. Before each chapter is submitted for publication, however, introductory information from Chapters 1 and 2, such as study site description and pertinent literature, will be inserted into the manuscript. Chapter 3 describes my study of channel morphology in the study tributaries to examine the connections between geomorphic processes operating on different spatial and temporal scales in response to human-induced change and to evaluate the applicability of an existing conceptual model of geomorphic adjustment in tributary streams. Chapter 4 presents my study of sediment dynamics in the study tributaries to understand the frequency and duration of sediment processes in adjusting tributaries. In Chapter 5, I examine the possibility of using channel morphology measurements and multi-response permutation procedure to examine sediment connectivity or transferal in tributary streams. Chapter 6, the conclusion of the dissertation, discusses overall spatial and temporal trends of geomorphic adjustment from the combined interpretation of the results of the channel morphology study from Chapter 3 in conjunction with the results of the sediment studies discussed in Chapters 4 and 5.

The Lower Hatchie River in West Tennessee

Current Geomorphic Dynamics and Related Human Disturbance History

The Hatchie River is a low gradient, large, alluvial river that begins in northern Mississippi and flows northward into western Tennessee where it travels approximately 322 km before joining the Mississippi River at a location 32 km north of Memphis (USGS, 1976). The Lower Hatchie River, which consists of the west Tennessee portion of the river, drains approximately 3,822 km^2 (Figure 1.1) (National Resources Conservation Service, 2001). Its headwaters, near Corinth, Mississippi, are channelized. However, the main stem of the river is unchannelized and exhibits a relatively natural state over its course in Tennessee.

The Lower Hatchie River in Tennessee is considered unique among alluvial rivers located in the Coastal Plain. Unlike many alluvial rivers that are part of the Lower Mississippi Valley, the Lower Hatchie River main channel escaped direct engineering modifications, such as channelization and leveeing. Therefore, the Lower Hatchie is highly valued as one of the few remaining undisturbed rivers of its type and location (The

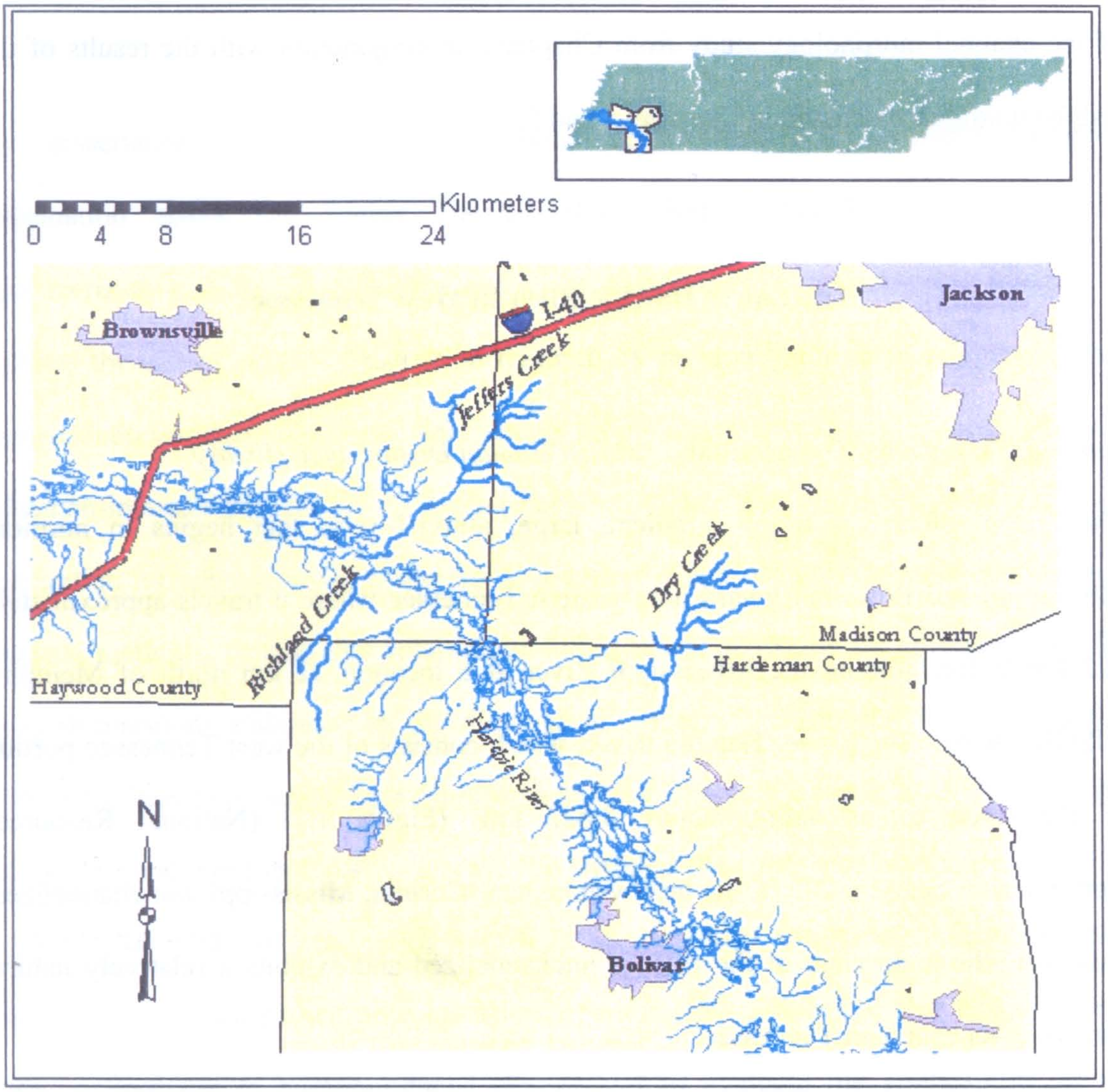

Figure 1.1: Study site location map, Lower Hatchie River Basin, west Tennessee.

Nature Conservancy, 2005). Because of its geographical location, relatively undisturbed physical condition, and the well–preserved 3,807 ha of bottomland forest within its watershed, the Lower Hatchie serves as habitat for over 200 species of migrating and wintering birds and 50 species of mammals (U.S. Fish and Wildlife Service, 2001). Two wildlife refuges are located within the Lower Hatchie Basin.

The perception of the Lower Hatchie River as undisturbed is only valid on the main stem and only to the extent that the river has not been subjected to direct modification by engineering works. In recent times, the channel depth has become shallower and flooding has increased (Soil Conservation Service, 1986). Changes in the bed elevation suggest increased sediment contributions from tributary streams to the main channel. Diehl (2000) identified sediment shoals forming in the main channel at confluences with some tributary streams. Because shoals are located on the main stem at confluences with tributary steams, this suggests that shoal-forming sediment is from the tributary streams.

Tributary streams of the Hatchie River, in both Mississippi and Tennessee, are heavily disturbed from historic land use activities in the watersheds and engineering modifications to their channels (Soil Conservation Service, 1986). Extensive land clearing and intense cultivation by early settlers in the upland areas of the basin stripped the top layers of soil and accelerated hillslope erosion processes, resulting in gully and rill formation in upland locations. Presently, these upland locations are forested with second growth vegetation and, when maintained in a deforested state, are used for pasture or hay production (National Resources Conservation Service, 1997).

During a 50-year period (approximately 1920 to 1970), many tributary streams of the Lower Hatchie River Basin were channelized to alleviate localized flooding of farmland. Flooding of farmland was related to a reduction of channel capacity due to accelerated aggradation of sediment originating from upland gullies and rills. In most cases, the channelization work was carried out by individual landowners (personal communication, Glenn Gallien, Tennessee Nature Conservancy, 2002).

I studied three tributary streams in the Lower Hatchie River Basin: Richland Creek, Jeffers Creek, and Dry Creek (Figure 1.1). All three of these tributaries were channelized by landowners, most recently during the 1970s. The lowermost reaches underwent channelization to the greatest extent because they are located in the most arable land and where farming is most extensive (personal communication, Lee Sammons, a Farm Bureau Century Farm Owner and Operator, 2003). Channelization efforts consisted of resectioning (widening and deepening the channel to increase channel capacity) and straightening. Because the channelization was done by individuals, no records exist that describe the geomorphic character and condition of streams prior to channelization other than anecdotal information supplied by a few landowners whose families retained land in the watershed for several generations. However, field investigations confirmed that many of the reaches exhibit a trapezoidal shape that is suggestive of channelization.

One of the study tributaries, Jeffers Creek, contains a sediment blockage that begins at its confluence with the Lower Hatchie River and extends approximately half a kilometer upstream (Figure 1.2). Sediment blockages (also referred to as valley plugs) form when aggradation diminishes the channel capacity to essentially zero. The channel is completely filled with sediment, so any additional sedimentation at the location spreads across the floodplain, eventually diverting flow and creating a new channel (Happ, 1975). An example from Hickory Creek, which is located in the Lower Hatchie, is shown in Figure 1.3.

The genesis of sediment blockages occurring in the Lower Hatchie River Basin is not entirely known as no quantitative analysis of this process has been undertaken. Specific aspects of sediment blockages that remain unknown include rates of formation and expansion, the role of coarse woody debris in establishing the blockages, and the discharge conditions required to transport substantial quantities of sediment and debris away from their source areas within the tributary streams.

The geographic location and spatial extent of sediment blockages has been documented in tributary streams and segments of the Lower Hatchie River main stem (Diehl, 2000). Sediment blockage formation appears to be a progressive process related to accelerated accumulation of sediment in low gradient reaches located near the confluences of tributary streams with the Hatchie River main stem (Diehl, 2000). The

Figure 1.2: Starting point of sediment blockage located at mouth of Jeffers Creek downstream of Bachelor Levee Road.

Figure 1.3: Channel completely filled by sediment blockage on Hickory Creek.

specific sources of sediment comprising the sediment blockages are many and potentially include sediment generated by historic land clearance and sediment generated by contemporary channel incision and bank failure processes related to channelization. Once established, sediment blockages grow in an upstream direction as woody debris and sediment accumulate behind the blockage. This process has been documented in other fluvial systems adjusting to human disturbances, specifically deforestation and intensive agriculture (Zierholz *et al.*, 2001).

Channelization and dredging activities possibly facilitate sediment blockage formation in tributary streams by increasing channel gradients, which results in an increase in the amount of energy available to transmit sediment to the Hatchie main stem (Diehl, 2000). Tributary streams contribute an estimated 582,400 metric tonnes of sediment to the Lower Hatchie each year (Soil Conservation Service, 1986). A sediment blockage formed in a channelized tributary that migrated into the Hatchie main stem, creating a blockage 6.44 km wide across the main channel and the floodplain (Diehl, 2000).

The sediment blockage located at the mouth of Jeffers Creek has resulted in the development of a seasonally flooded bottomland that is progressively developing into a full-fledged wetland. Although accelerated aggradation appears to be involved in the formation of the blockage and seasonally flooded bottomland, the formation and/or maintenance of the seasonally flooded bottomland is also probably related to beaver damming that occurs in the river segment (Figures 1.4 and 1.5). The seasonally flooded

Figure 1.4: Evidence of beaver activity adjacent to sediment blockage downstream of Bachelor Levee Road in Jeffers Creek.

Figure 1.5: Evidence of beaver activity, located near confluence of Jeffers Creek and Lower Hatchie River, upstream of Eustonale Road.

bottomland that currently exists is changing plant communities in the vicinity and does not accommodate hardwood bottomland forests. The U.S. Fish and Wildlife Service estimates that more than 40.5 ha/year of hardwood bottomland forest are lost in the Hatchie from flooding related to accelerated sedimentation. The age and long-term formative processes of hardwood bottomlands currently located in the Lower Hatchie Basin are largely unknown. The possibility exists that the relatively drier hydrologic regime that supported this community during the last century was either enhanced or entirely established by changes to surface hydrology that occurred with human settlement, specifically artificial drainage of bottomlands. This idea has been proposed to explain long-term changes in vegetation in the Wolf River Basin, south of the Hatchie River Basin in Tennessee, which also has a substantial human disturbance legacy that includes land-use change and channelization (Shankman and Smith, 2004).

The three counties, Hardeman, Haywood, and Madison, in which the study streams are located have similar relief and land use characteristics. Although located in the Coastal Plain physiographic subprovince, the three counties do have some gentle relief. Upland locations have been heavily dissected by fluvial processes, resulting in rolling topography in headwater areas that grade into flat, open expanses of river floodplains as the tributary streams approach the Lower Hatchie Basin. Surface hydrology has been altered to a great extent from conversion of forested land to agricultural land. West Tennessee was settled by European settlers beginning around 1820 after the Chickasaw Purchase occurred in 1818 (National Resources Conservation Service, 1997). Settlers cleared the forests for cotton cultivation, including upland locations, which enhanced fluvial dissection of the landscape by creating gullies and rills. Historic gullies and rills have since reforested, but erosion problems persist. For example, the National Resources Conservation Service estimates that at least 50% of Hardeman County is affected by erosion, particularly in upland locations, and that soils located on upland slopes have lost anywhere from 3.3 cm to 10.0 cm of topsoil due to cultivation (National Resources Conservation Service, 1997). The major land use in the three counties remains agriculture, mainly forestry and crop (cotton and soybean), but because of the extensive upland erosion, agriculture is mainly confined to low-lying floodplain areas that have the only remaining productive soils (National Resources Conservation Service, 1978; 1995; 1997).

The study streams are not gauged, but are known to have very little flow year-round, except in the spring when the most precipitation is received (National Resources Conservation Service, 1997). During the summer, autumn, and winter, stream channels are mostly dry. This may be related to water table lowering either by anthropogenic activities or unknown natural processes. In addition, most of the tributary streams with a channelization history have a flashy response during storm events, in part because of the increased gradient that came with channelization, but also because of increased runoff from land clearance and ditches that expediently drain agricultural fields.

The presence of sediment blockages and gully networks in some tributary streams of the Lower Hatchie suggests that these streams are responding to disturbance, probably related to land-use changes and channelization. Because of the Hatchie River's ecological significance, many private, state, and federal agencies are planning to restore riparian habitat lost to the ongoing aggradation. Understanding the degree to which geomorphic adjustment and/or recovery have already occurred will be important to the design of any ameliorative measures used in the Lower Hatchie or other drainage basins with similar watershed issues.

Climate

The climate of west Tennessee can be described as humid subtropical, with mild winters, hot summers, and precipitation occurring throughout the year. Table 1.1 provides a summary of temperature and precipitation characteristics for Bolivar, TN, located within the Lower Hatchie Basin. Average daily maximum temperatures peak in July and August (approximately 32 °C), while average daily minimum temperatures occur from December through February (ranging from -1 to -3 °C). Precipitation occurs throughout the year, and average monthly precipitation values range from 7.7 cm to 14.3 cm. The highest average monthly precipitation occurs in the late winter through the spring (December through May) and lowest average monthly precipitation occurs in the summer and autumn (June through October). Precipitation in the form of snowfall occurs infrequently and not in substantial quantities, less than 10.0 cm for the average yearly total (National Resources Conservation Service, 1997). Because precipitation occurs throughout the

Table 1.1: Average climate characteristics for Bolivar, Tennessee from 1961–1990 (modified from National Resources Conservation Service, 1997).

Month	Avg. Daily Maximum Temperature (°C)	Avg. Daily Minimum Temperature (°C)	Avg. Monthly Precipitation (cm)
Jan	8.3	- 3.2	10.1
Feb	11	- 1.3	11.4
Mar	16.6	- 3.8	13.9
Apr	22.2	8.9	13.4
May	26.3	13.4	13.7
Jun	30.5	17.9	9.3
Jul	32.3	20.1	9.4
Aug	31.8	18.9	8.8
Sept	28.5	15.3	10.1
Oct	23.1	7.9	7.7
Nov	16.5	4.1	12.3
Dec	10.6	- 0.9	14.3

year, the potential exists for year-round potential for runoff and soil erosion to develop. The peak daily precipitation occurs in the late winter and early spring when natural vegetation is dormant and crops are not mature. As a result, this time of year could be the most geomorphologically active time of year, with increased sediment input to the channel from soil erosion and more sediment transport occurring because of larger stormflows created by increased runoff.

Geology

The Lower Hatchie Basin lies within the Lower Mississippi Embayment and, as a result, contains a variety of fluvial and coastal deposits. The geology is mainly composed of Holocene fluvial deposits, Pleistocene/Pliocene loess and fluvial deposits, and Tertiary Coastal Plain sediments (Miller, 1974; Luther, 1977; National Resources Conservation Service, 1997). Most of the Holocene alluvium is from the Lower Hatchie River and its tributaries and is found in active floodplains. The Pleistocene loess deposits range from 9 cm to 152 cm thick, but are thinnest on uplands and hilltops due to erosion. The most extensive geologic material in the three-county study area is the Pleistocene/Pliocene fluvial deposits (National Resources Conservation Service, 1978; National Resources Conservation Service, 1995; National Resources Conservation Service, 1997). These deposits occur in upland areas and hilltops and consist of quartz-rich sand, some silt and clay, and gravel. Also found in upland areas and hilltops are Tertiary-aged Coastal Plain sediments, including the Claiborne and Wilcox Formations. The Claiborne Formation consists of quartz-rich sand with some lenses of kaolinitic clay. It also contains the coarsest sand in the basin, rounded gravel, and ferringous, tabular sandstone formed by groundwater fluctuations (National Resources Conservation Service, 1997). The Wilcox Formation is composed of fine sand, silt, and clay with some interbedded and interlensed units of lignite, kaolin, and siderite. Some of the sand in the Wilcox Formation is micaceous (National Resources Conservation Service, 1997).

Field observations suggest that Richland and Jeffers Creek have exposures of the Claiborne Formation in their headwater contributing areas (Figure 1.6), and that the Wilcox Formation is exposed in the headwater contributing areas of Dry Creek (Figure 1.7). The most likely sources of bedload material, specifically gravel particles, in the three study streams are the fluvial units of the Wilcox Formation.

The relative homogeneity of geologic material found in the watersheds of the three study tributaries makes identifying sediment sources based on particle size and lithologic characteristics very difficult. In addition, the unconsolidated nature of the geologic material increases the potential for erosion to occur.

Soils

The soils of the three study tributaries are primarily loamy, ranging from clay/silty loams to sandy loams. Soils vary with topographic location and proximity to active river channels because of changes in parent material (Figure 1.8) (National Resources Conservation Service, 1978; National Resources Conservation Service, 1995; National

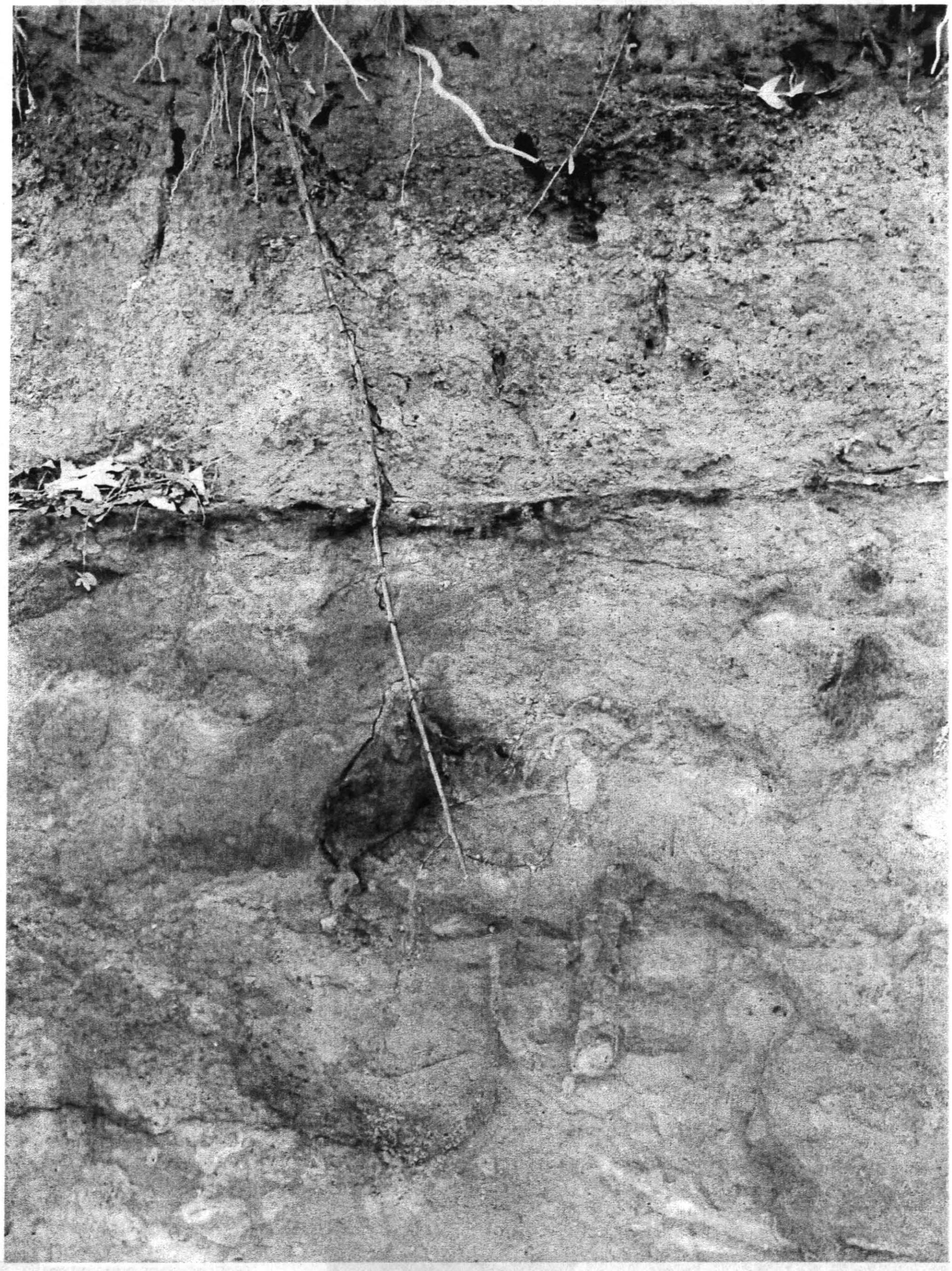

Figure 1.6: Possible exposure of Wilcox ferringous sandstone unit in Jeffers Creek downstream of Woodland Road.

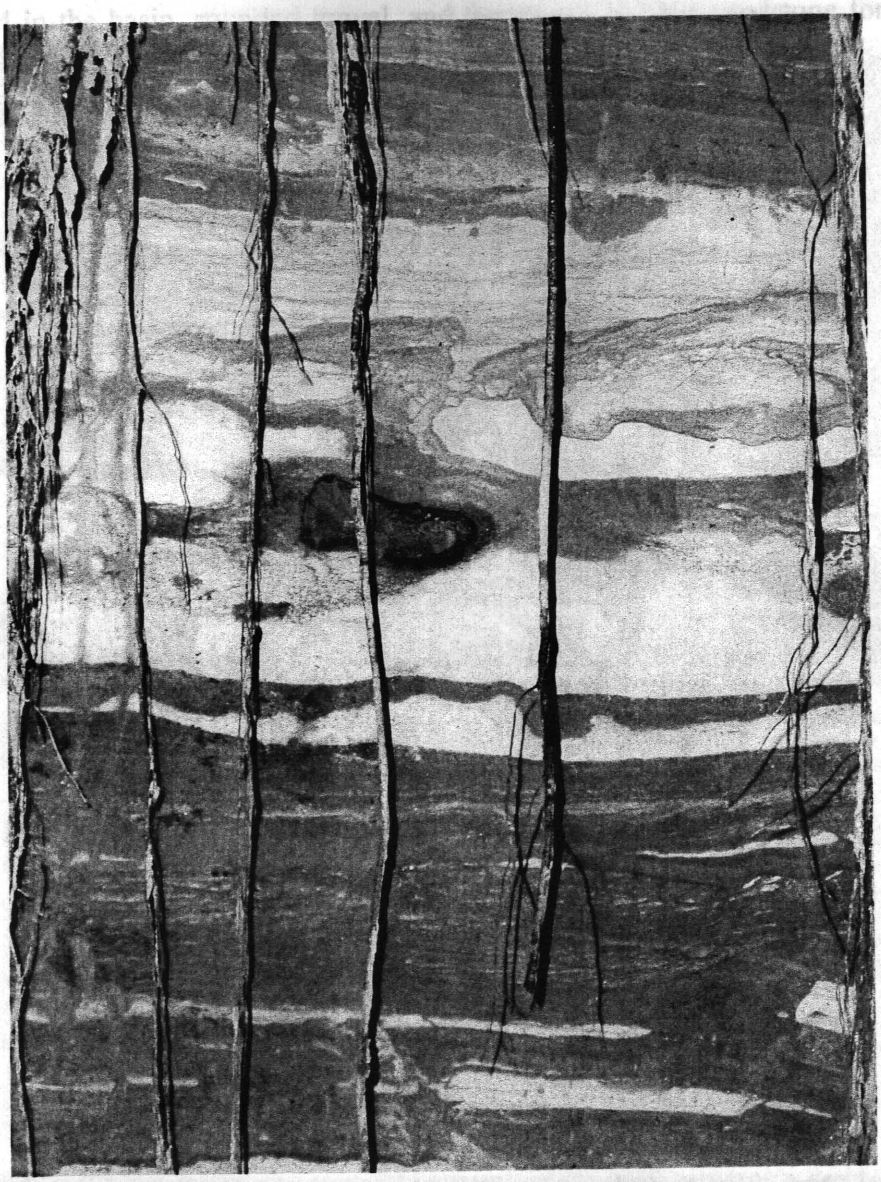

Figure 1.7: Possible exposure of Claiborne Formation in Dry Creek downstream of John Green Road. Exposure is approximately 2 m in height.

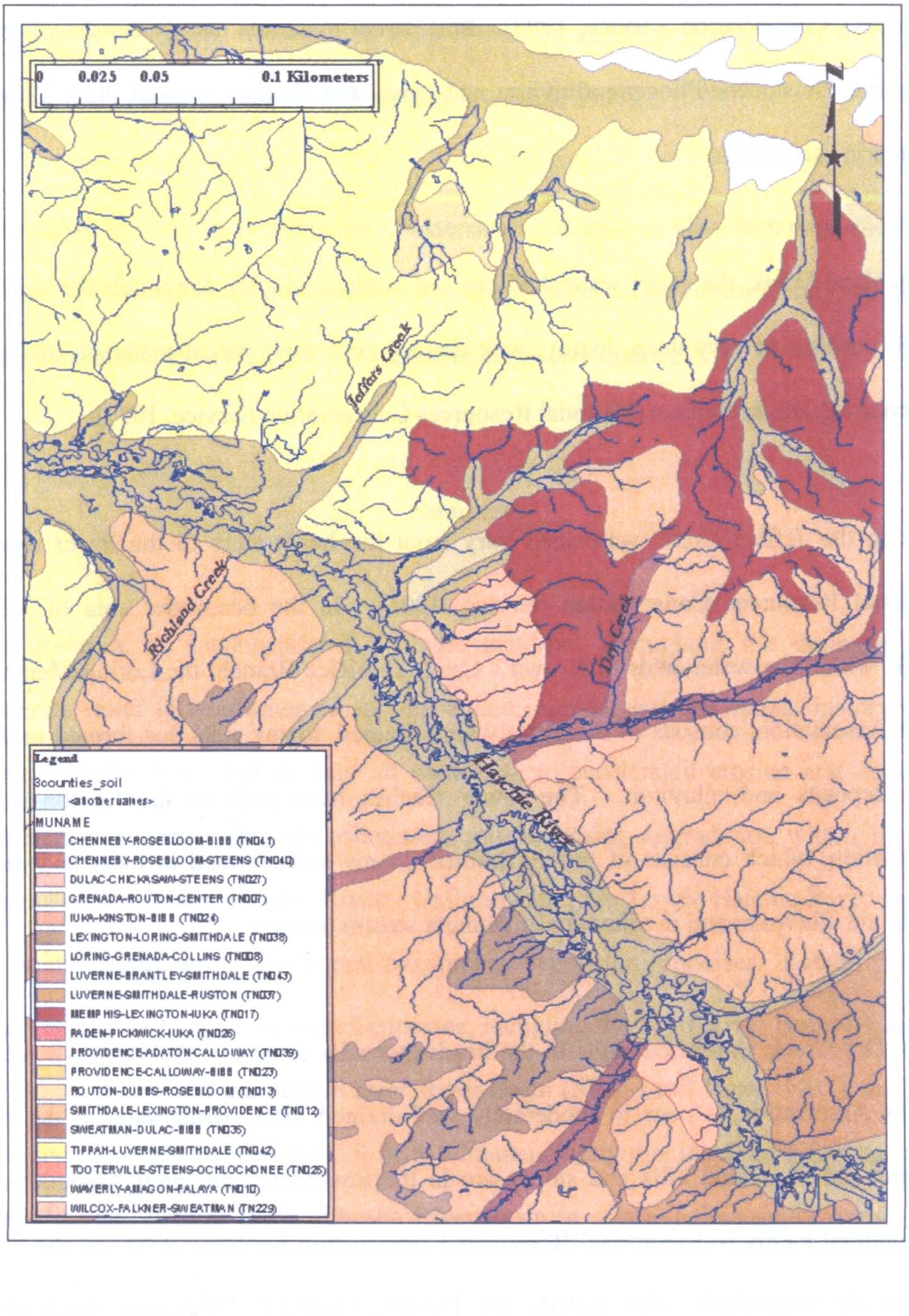

Figure 1.8: Map of study watersheds showing the location of major soil associations.

Resources Conservation Service, 1997). Soil parent materials mainly consist of recent alluvium, Pleistocene/Pliocene alluvium and loess, and Tertiary Coastal Plain alluvium and marine sediments.

In Richland Creek, the entire watershed has soil in the Lexington-Smithdale Association, which consists of very deep, loamy, well-drained soils with parent materials of fluvial and coastal plain sediments (National Resources Conservation Service, 1997).

Soils in the Jeffers Creek watershed vary from the headwaters to the lower reaches (National Resources Conservation Service, 1995). In the headwater area of Jeffers Creek, within the watersheds of Brown's Creek and Rice Branch, the Loring-Memphis-Adler Association, consists of moderately well-drained, loamy soils that formed in thick loess deposits and alluvium. The lower reaches have soils in the Routon-Dubbs Association, which consists of poorly drained, loamy soils formed in loess and recent floodplain alluvium, and in alluvium of younger stream terraces.

In the Dry Creek watershed, soils in the headwater area consist of the Falaya-Waverly-Collins Association, a poor to moderately well-drained loam, while soils in the river bottoms and in upland hills and slopes are in the Smithdale-Lexington Association, a well-drained loamy soil (National Resources Conservation Service, 1978). In the lower half of the watershed, soils include the Luverne-Smithdale-Chickasaw Association, which is a very deep, well-drained loam formed in clay-rich and loamy Coastal Plain sediments (National Resources Conservation Service, 1997).

Overall, soils found in the three study watersheds are quite similar, with most soils being loams. Soils found in upland locations with higher sand content drain readily, while soils in river bottomlands with higher clay content are poorly drained.

Summary

The presence of unconsolidated geologic materials throughout the drainage basin, moderate relief in headwater areas, year-round rainfall, and the human history of the Lower Hatchie River Basin, may all contribute to accelerated erosion and deposition processes occurring within its tributaries, and increasing aggradation within the main channel of the Lower Hatchie River. Unfortunately, the Lower Hatchie River Basin is not unique regarding its accelerated erosion and deposition processes. Rather, the basin is representative of rivers in west Tennessee, including the Wolf River Basin (Shankman and Smith, 2004) and the Forked Deer River Basin (Simon and Hupp, 1987), and many other rivers in the Southeastern U.S. with a human history that involves deforestation and channelization, such as the Yalobusha River Basin in central Mississippi (Simon, 1998; Downs and Simon, 2001).

CHAPTER 2

Understanding the Fluvial System

Introduction

Because this dissertation examines ongoing adjustment processes in tributary streams with a history of land use change and channelization, a review is necessary concerning how rivers function as fluvial systems and the many ways that fluvial systems respond to human-induced change.

The Fluvial System

Fluvial systems are understood to exist in a state of dynamic equilibrium (Hack, 1960). The independent variables that comprise fluvial systems, sediment load and discharge, vary about a mean state determined by other factors, including climate, tectonics, geology, land use, and random disturbance. Individual components of a fluvial system are dynamically linked such that a change experienced in one of the variables begins a set of compensatory adjustments that sometimes develop into positive and negative feedback loops (Schumm, 1977). For example, the amount and type of sediment and discharge determine channel morphology (Dunne and Leopold, 1995). Channel size evolves to accommodate the dominant discharge, which is primarily determined by the climate of the basin. Channel sediment indirectly affects channel morphology by consuming energy in sediment transportation processes that could otherwise be used in bank erosion processes, which could increase channel width. With increasing size or amount of sediment in the channel, the amount of energy necessary to transport the material increases. A decrease in the energy available for sediment transport may result in sediment deposition, which, if prolonged, can reduce channel depth, making the channel wider and shallower, for example. Channel morphology represents the current balance of discharge and sediment transport requirements and the amount of energy left over for other geomorphic processes, such as bank erosion, for a particular time and place in the system (Lane, 1955).

The Effects of Human-Induced Disturbance

Human-induced change in fluvial systems can be related to a wide variety of human activities and can result in changes to cross-sectional shape, longitudinal profile, sediment dynamics, and watershed hydrology. In general, human disturbance in fluvial systems involves direct modification of the channel, such as engineering works related to channelization, or indirect modification occurring outside of the channel, such as deforestation, that result in a change in surface hydrology and sediment contribution to the channel (Knighton, 1998).

Channel aggradation is a common adjustment to anthropogenic disturbances, including deforestation (Brooks and Brierley, 1997), logging (Stover and Montgomery, 2001), and urbanization (Nelson and Booth, 2002). Introduced sediment can be transported with the natural load and eventually results in an increase in vertical accretion (floodplain storage) rates (Knox, 1987; Brooks and Brierly, 1997). If the material is incorporated into the channel load, it can also cause deposition within the channel (Madej, 1995) and, over a longer period, makes the channel wider, shallower, and less sinuous (Madej and Ozaki, 1996; Brooks and Brierley, 1997). Aggradation can also initiate lateral migration processes when unconsolidated material becomes bedload because the material can be stored in shifting bar complexes (Saucier, 1984). As a result of aggradation, bankfull widths can increase by as much as 100% compared to pre-deforestation bankfull width (Knox, 1977). A decrease in channel capacity can also occur, however, such as in the case of direct addition of mining spoil, and this can lead to flooding downstream (Wildman, 1981).

A reduction or increase in the quantity of discharge (or runoff) in a system can also affect channel morphology. The reduction of discharge as a result of damming can cause channel narrowing (decreased channel width and channel capacity) (Williams, 1978; Petts, 1979). The extent to which narrowing occurs may also depend on the erodibility of channels and may be limited by the development of channel bed armoring (Williams and Wolman, 1984; Xu, 1990; 1996). When discharge increases due to increased runoff from activities such as deforestation, the frequency of smaller magnitude floods can increase (Knox, 1977; 1987). Increased runoff related to vegetation removal (Madej, 1995; Nolan and Maroon, 1995) and from soil compaction by machinery (Raper, 2005) and cattle (Kauffman and Krueger, 1984) can also make the system more easily changed by smaller magnitude storms. Urbanization also increases runoff, shortens lag times, and increases the magnitude of peak discharges (Hollis, 1975). The increase in flood frequency and magnitude from urbanization can cause channel enlargement through an increase in the bankfull cross-sectional area (Roberts, 1989), but can also cause an increase in the mean depth and a decrease in bankfull width due to an increase in overbank deposition related to flooding (Leopold, 1973).

In most cases, fluvial geomorphic adjustment processes are not instantaneous but may occur long after the actual disturbance event, depending on which components of the system are affected and on their location within the system (Schumm, 1977). Adjustments may exhibit a time lag related to sediment dynamics. If sediment is temporarily stored within the system, then processes of erosion, transport, and deposition of sediment may be prolonged as a result. For example, erosion related to enhanced surface runoff from deforestation can mobilize material from hillslopes that can be stored as colluvium at the base of slopes, as alluvium in floodplains, or as alluvium in channel deposits (Trimble 1974, 1983). The sediment may stay in storage for a period of years before being re-incorporated into the channel system. Mining waste and spoil can require longer intervals of time to be transported out of the system because of a lack of competent discharge (Lewin and Macklin, 1987; Nicholas *et al.*, 1995).

Fluvial adjustments may also take a long time because disturbance in one part of the system can be translated over time upstream or downstream as part of a complex response (Schumm, 1977). Translated adjustments may amplify or decrease in magnitude with distance from the location of the original disturbance, resulting in a cumulative effect at some locations. For example, the initial phases of urbanization, when the most sediment is available, can cause channel narrowing from aggradation, but channel enlargement can occur when available sediment is exhausted, and the magnitude and frequency of floods increases (Arnold *et al.*, 1982). A channel may first widen after mining wastes are introduced, but the channel can narrow and incise, as mining spoil is exhausted as a sediment source (Macklin and Lewin, 1989). Downstream of dams, channel beds can incise because water exits the dam without sediment load (Williams and Wolman, 1984). Once set in motion by a decrease in sediment load from damming, bed incision can migrate downstream and initiate incision in tributary streams, which migrates upstream into headwater areas (Germanoski and Ritter, 1988).

Effects of Channelization

One of the most profound forms of human disturbance of fluvial systems is river channelization. Brookes (1985) estimates that more than 26,500 km of river length was channelized in the United States alone during the 50-year period from 1930 to 1980. Several direct modifications of channel shape and form can occur with channelization. Most often the channel is straightened, which increases stream gradient by creating short flow paths. In some cases, the whole channel or at least segments are "resectioned," which involves widening and/or deepening the channel to increase channel capacity in an effort to reduce flooding (Knighton, 1998).

Because rivers function as systems with internal and external connections between the various components, the effects of channelization can be transmitted upstream and downstream of the actual channelized segment (Brookes, 1987). Simon (1992) surmised that most low-energy alluvial systems respond to channelization by making vertical adjustments, including incision, channel aggradation, and vertical accretion. The physical location of the area of maximum disturbance (AMD) (i.e., the channelized segment) acts as a fulcrum for aggradation and degradation processes, with net degradation occurring upstream of the AMD and net aggradation occurring downstream of the AMD (Simon, 1989, 1992). Channel "straightening" results in increased flow velocity and transport capacity, which can cause incision and the establishment of a headward-migrating knickpoint upstream of the channelized segment, while downstream of the channelized segment, where reach gradient is lower, channel aggradation can develop (Brookes, 1995). Channel incision instigated by channelization can create bank instability by first deepening the channel so that bank heights are oversteepened. After the passage of the knickpoint, banks remain unstable for years due to undercutting of the channel banks as the channel widens (Simon, 1991; Yodis and Kesel, 1993). Channel widening that occurs as a direct consequence of resectioning reduces stream power and can instigate channel deposition in the form of berm development inside the channel as the stream works toward regaining its original width (Brookes, 1988).

Geomorphic Adjustment Rates

Rates of adjustment (recovery) are poorly understood because most fluvial systems have long and complicated histories, and separating the effects of one event from another is difficult (James, 1999). Recovery times for morphologic changes due to flooding, however, appear to be relatively short (Graf, 1977), while changes to sediment dynamics in anthropogenically disturbed systems may require longer periods, particularly if engineering modifications, such as riprap, exist as these increase the resistance factors associated with their presence (Thornes and Brunsden, 1977). Recovery from anthropogenic disturbance is estimated to require more than 40 years (Petts, 1989), but few studies exist to validate this estimate. Simon and Hupp (1987) measured a recovery time of 50 years for bank stabilization in channelized alluvial rivers, as inferred by the rate of vegetation establishment on banks. James (1999) warned, however, that estimates of fluvial recovery are greatly underestimated because they are mainly based on a return to pre-disturbance channel morphology, which often does not fully reflect stabilization of sediment dynamics. Sediment may be stored in floodplains or in channel features for long periods and may cause episodes of aggradation well into the future.

The issue of what constitutes recovery also remains debatable. On a very basic level, recovery can be considered the cessation of adjustment, with the onset of recovery delineated by a shift from degradation to aggradation (Hupp and Simon, 1991). Recovery is also considered to be a return to pre-disturbance conditions or the establishment of a new equilibrium condition (Magilligan and Stamp, 1997).

Summary

The geomorphic response of systems to different types of human-induced change is not well understood, mainly because of complexities inherent to fluvial systems. Existing research in disturbed fluvial systems emphasizes the importance of discharge and sediment load on geomorphic adjustment processes (Knighton, 1998). However, the role of internal system dynamics, such as sediment processes, and reach-scale dynamics in determining the timing and location of geomorphic adjustment processes remains unclear.

CHAPTER 3

Geomorphic Adjustment in Tributary Streams

This chapter is a manuscript in preparation for submission to the journal *Geomorphology*. In an effort to avoid repetition in the dissertation, parts of Chapter 1 that describe the physical characteristics and human history of the study site are omitted in the following discussion, but prior to submission will be included in the final manuscript.

Introduction

In Chapter 2, I reviewed the multiple changes that can occur in fluvial systems as a result of human-induced disturbance, including altered channel shape, altered discharge characteristics, and accelerated sediment dynamics (sediment production, storage, and transport). Based on the review in Chapter 2, fluvial geomorphic responses to human-induced change can be divided into three broad categories, which are not mutually exclusive or exhaustive of all possible responses but are commonly observed in most systems: (1) changes in channel shape and sediment dynamics related to alteration of discharge, (2) accelerated sediment dynamics related to site specific characteristics, bank erosivity for example, and (3) system-wide responses related to the propagation of changes in upstream and/or downstream directions. Each of these broad categories of change can operate at different spatial and temporal scales. What is lacking from our understanding of fluvial geomorphic response to human-induced change is an understanding of the connections between the three broad categories of geomorphic response. Understanding the connections between the different categories of geomorphic response identified, both conceptually and physically, is pivotal to understanding how geomorphic changes actually occur over time and across space in response to human modifications, predicting future change, and understanding the potential for physical changes made at point locations or for limited amounts of time to have broader implications.

Tributary streams of the Lower Hatchie Basin (LHR), with their complex histories of land use change and multiple phases of channelization and dredging activity, provide an excellent setting in which to examine questions of geomorphic adjustment to human-induced change. The three tributary streams I studied have an extensive channelization history (detailed in Chapter 1). Though poorly documented, the history of channelization in these tributary streams includes multiple episodes of channelization, occurring primarily in the lowermost reaches, and periodic dredging of channelized reaches, meaning there were multiple periods of disturbance.

In this study, I use channel morphology measurements to examine the connections between geomorphic processes operating on different spatial and temporal scales in response to human-induced change in three tributary streams of the LHR Basin — Richland, Jeffers, and Dry Creeks. The following questions regarding geomorphic adjustment are addressed:

1. What is the current state of channel morphology in LHR tributary streams post-channelization?
2. What are the geomorphic processes that connect channel shape and sediment dynamics (sediment production, storage, and transport) in the tributary streams?
3. Do reach-scale geomorphic processes related to channel shape and sediment dynamics have any implications for system-wide response to change in tributary streams, and, if so, what processes are involved?

In addition, I examine the ability of an existing conceptual model, the channel evolution model, of geomorphic adjustment to describe and explain geomorphic adjustment processes occurring in three tributary streams located in the LHR Basin. Questions regarding the conceptual model, which is described in more detail in the methods section of this chapter, include the following.

4. Does the Channel Evolution Model (CEM) (Simon, 1994), an existing conceptual model of geomorphic adjustment to channelization developed in larger river systems, incorporate all major geomorphic adjustment processes?
5. How applicable is the CEM in tributary streams with a history of multiple disturbance periods?

Methods

Channel Morphology

I measured channel shape and made bank observations in each of the three study tributaries. The hydraulic geometry or cross-sectional shape of a channel helps establish the hydrologic, geomorphic, and biological characteristics of a fluvial system. Cross-sectional shape determines the size and shape of flood waves (Western *et al.*, 1997) and the sediment transport capacity (Richards, 1982; Chang, 1988). Cross-sectional shape affects the biota within fluvial systems by determining habitat condition (Lamouroux *et al.*, 1992, 1995; Lamouroux, 1998; Stewardson and McMahon, 2002) and by operating in conjunction with geomorphological processes to influence species diversity (Giller *et al.*, 1994; Huston, 1994; Palmer *et al.*, 1997; Rhodes *et al.*, 2003). Existing research that examines channel shape focuses on the relationship between discharge and cross-sectional shape variables (Leopold *et al.*, 1964). Few studies have examined the role of sediment load in determining cross-sectional channel shape or have been able to explain why cross-sectional shape can vary substantially within a single reach (Stewardson, 2004).

Study Site Locations and Selection

I surveyed cross-sectional channel shape in 34 reaches in the three study tributaries using an auto-leveling laser survey station. The locations of channel morphology survey sections are shown in Figure 3.1. I selected study reaches by a multi-step process. First,

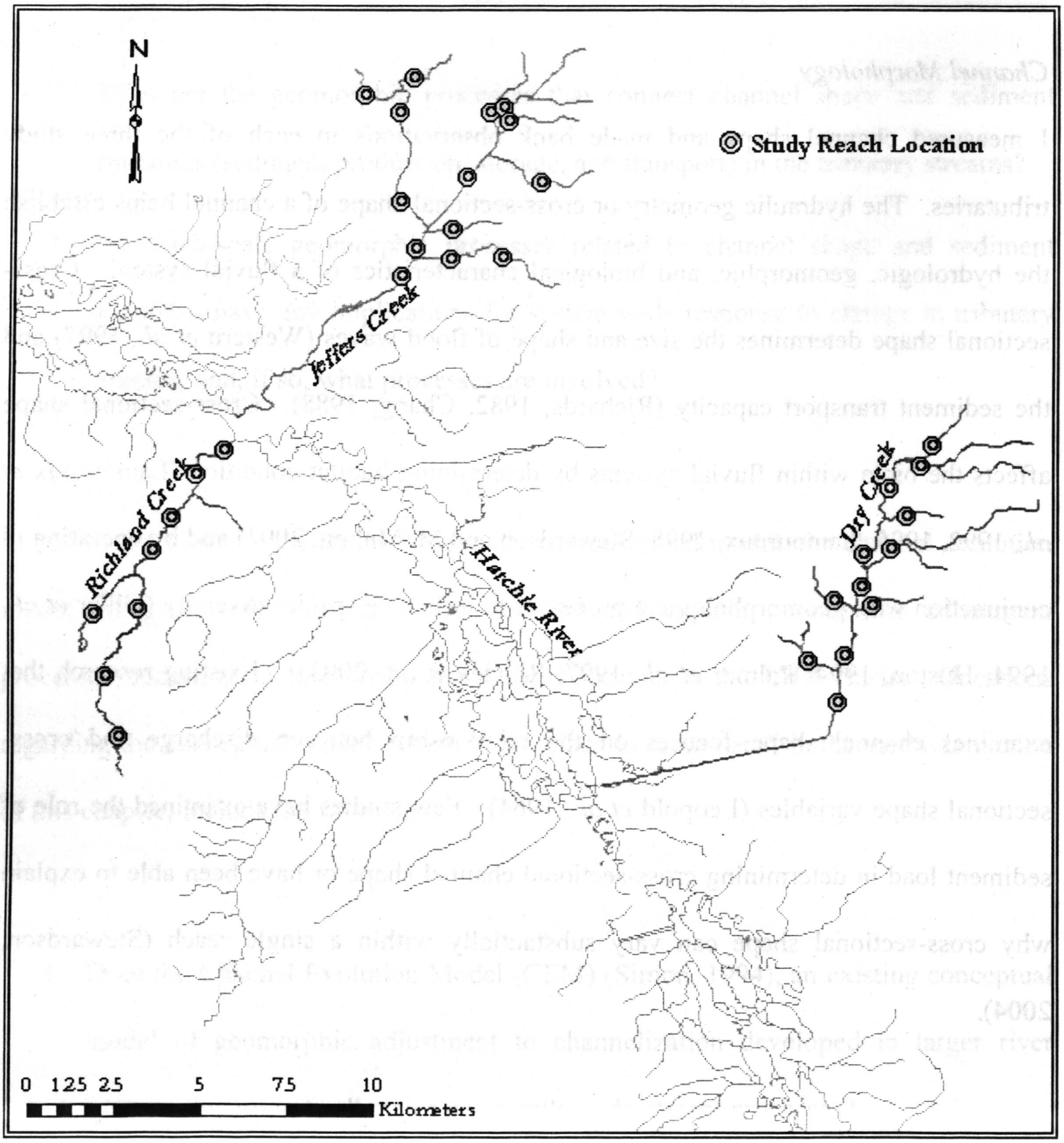

Figure 3.1: Locations of channel morphology survey reaches in the study tributaries. The Hatchie River flows from the southeast to the northwest.

I used ESRI ARCMap 8.3 geographic information system software to divide each of the study tributaries into smaller sub-watersheds. Within ARCMap, I used the ARCHydro extension to model surface water flowpaths and delineate drainage divides on 10 m digital elevation models (DEM) for Hardeman, Haywood, Denmark, Hillville, and Madison 7.5' topographic quadrangles produced by the United States Geological Survey (Tennessee Spatial Data Server, 2003). The ARCHydro DEM analysis identified stream segments larger than several hundred meters with different contributing areas (sub-watersheds). Of all the stream segments identified by the DEM analysis, I selected a subset of segments consisting of one from each watershed and those located upstream and downstream of major stream junctions to examine in the field. I then walked the entire length of each stream segment and surveyed one reach within each stream segment. The reaches surveyed were each approximately 100 m in length and exhibited geomorphic features and processes typical, or as close to typical as possible, of the entire stream segment. When choosing reaches, I avoided reaches located near bridges.

Field Measurements and Observations

Within each reach, I measured cross-sectional shape and made bank observations at three locations - a cross-section at the lower end of the reach, a cross-section in the middle of the reach, and a cross-section at the upper end of the reach. At the middle cross-section, referred to as the "primary cross-section," I made measurements that extended out of the channel and onto the pre-channelization floodplain. At the lower and upper cross-sections, I took measurements until reaching what I considered bankfull, which because of the entrenched state of the streams was located well below the tops of banks.

In addition to cross-sectional shape, I also measured at each cross-section channel depth (relative to the tops of the banks) and channel width (from bank edge to bank edge), both at regular intervals based on the width of the cross-section. I used the width and depth measurements to calculate "top-of-bank" cross-sectional area (Figure 3.2). I measured bed slope along the length of the entire study reach by measuring the change in elevation of the channel bed at the lower cross-section and at the upper cross-section within the reach.

I made observations of bank processes and properties and channel sediment storage at the primary cross-section (middle cross-section). I measured and described bank shape (linear, convex, or concave), bank angles (upper, middle, and lower), presence and type of mass failures, and texture of bank material of both banks at each primary cross-section. I used a bank survey protocol developed by Thorne (1998). At the primary cross-section, I measured the depth of sediment at regular intervals across the channel using a 1 m long piece of rebar. I pounded in the rebar with a hammer until the bar could not be inserted any farther, which I interpreted as an indication of reaching the channel bottom. If the sediment depth was less than 1 m, I recorded the exact depth, but if the sediment depth was greater than 1 m, I recorded depth as greater than 1 m. I sampled the channel bed–

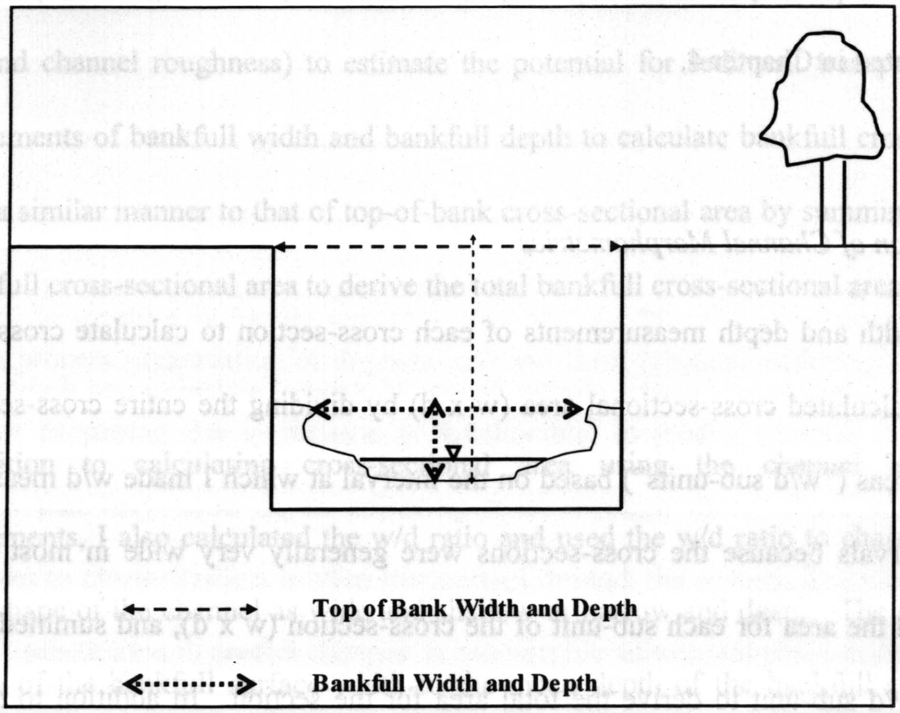

Figure 3.2: Schematic that shows the difference between top-of-bank width and depth measurement from bankfull width and depth measurement.

load of each primary cross-section for particle size analysis (PSA), the results of which are presented in Chapter 4.

Calculation of Channel Morphometrics

I used width and depth measurements of each cross-section to calculate cross-sectional area. I calculated cross-sectional area (w x d) by dividing the entire cross-section into smaller areas ("w/d sub-units") based on the interval at which I made w/d measurements (1 m intervals because the cross-sections were generally very wide in most cases). I calculated the area for each sub-unit of the cross-section (w x d), and summed the areas of each w/d sub-unit to derive the total area for the section. In addition to measuring widths relative to the bank edges and depths relative to the bank tops, I also made bankfull w/d measurements, which I measured relative to field indicators of bankfull stage (Figure 3.2).

Bankfull discharge is considered to be the discharge at which the channel-holding capacity reaches its maximum. Beyond this stage, the river overflows its banks and floods. However, in deeply incised channels, such as the study tributaries in the Lower Hatchie River Basin, bankfull discharge is actually retained within the incised channel, at some depth below the top of the banks. Bankfull discharge is often assumed to occur on average every 1.5 years, suggesting that it is a discharge of moderate magnitude that occurs with relative frequency (Leopold *et al.*, 1964). Given its frequency and magnitude, some sediment transport processes must occur during bankfull stage conditions, and therefore can be used in conjunction with other variables (such as channel slope and channel roughness) to estimate the potential for sediment transport. I used measurements of bankfull width and bankfull depth to calculate bankfull cross-sectional area in a similar manner to that of top-of-bank cross-sectional area by summing sub-units of bankfull cross-sectional area to derive the total bankfull cross-sectional area.

In addition to calculating cross-sectional area using the channel morphology measurements, I also calculated the w/d ratio and used the w/d ratio to characterize the overall shape of the channel as wide and shallow or narrow and deep. The w/d ratio is the ratio of the bankfull surface width to the mean depth of the bankfull channel and reflects the relative asymmetry of channel shape due to the storage of sediment within the cross-section (Leopold *et al.*, 1964). A large w/d ratio (generally defined as > 10) indicates a wide, shallow channel with extensive point bar development that constricts the thalweg to one side of the channel, while a small w/d ratio (generally defined as < 10) indicates a narrow, deep channel with restricted bar formation due to less low energy locations being available for sediment deposition (Markham and Thorne, 1992; Knighton, 1998). I interpreted w/d ratios considerably > 10 as being suggestive of cross-sectional asymmetry caused by the presence of well-developed bar deposits. I used top-of-bank width and depth measurements to calculate the w/d ratio: width of the cross-section (from bank edge to bank edge) divided by the depth of the cross-section (relative to the top of the channel banks). I chose to use top-of-bank w/d ratio in this way because of the effect bank failures at the top of channel banks can have on channel shape. Had I used the bankfull w/d ratio, my analysis of the overall shape of the channel would neglect any effect of bank failure in determining channel shape because bankfull surfaces, for the most part, occur below the height of bank failure surfaces.

I separated study reaches with similar w/d ratios into groups as a means of identifying reaches that have experienced a similar degree of channel widening and deepening. To identify reaches with similar w/d ratios, I compared all of the w/d ratios and identified natural breaks. I identified natural breaks by sorting the w/d ratios in descending order and applying a simple running difference calculation. The running difference calculation involved subtracting the w/d ratios from each other, beginning with the largest w/d ratio measurement and the second largest and then continuing through the ratios in descending order. This calculation determines the difference in size between the ratios and results in n–1 samples. I interpreted ratio differences of two or more to indicate a significant change in channel size.

Channel Evolution Model (CEM)

I applied a conceptual model of geomorphic adjustment developed for alluvial channels adjusting to channelization to identify and describe the degradational and aggradational geomorphic adjustment processes occurring in the study reaches in response to channelization and historic land use change.

The Channel Evolution Model (CEM) developed by Simon (1994) identifies six stages of channel evolution based on the spatial and temporal distribution of geomorphic processes, specifically aggradation and degradation, as inferred from channel morphology (cross-sectional area, thalweg location, and bank stability or instability) that dominate individual reaches or geomorphic zones. The CEM emphasizes interactions between process (aggradation or degradation) and form (channel widening due to bank failure or deepening due to incision or knickpoints) to predict changes in shape and processes that may occur in an adjusting reach through time. Because base level adjustment to channelization is often transmitted through the system, Simon uses "space for time" substitution to predict changes in geomorphic adjustment processes and channel morphology in a given reach by examining the physical location of the reach in the watershed relative to the area of maximum disturbance (AMD) or the point of channelization. Six stages of adjustment are outlined in the CEM. The processes and channel shapes associated with each stage are shown in Figure 3.3. Processes involved in each stage include the following:

Stage I: Premodified Stage - an undisturbed reach;

Stage II: Constructed Stage - construction of a new channel with steepened, heightened, and linear banks;

Stage III: Degradation Stage - high energy flows erode basal surfaces and undercut banks, but bank failure does not occur because critical bank height has not been exceeded;

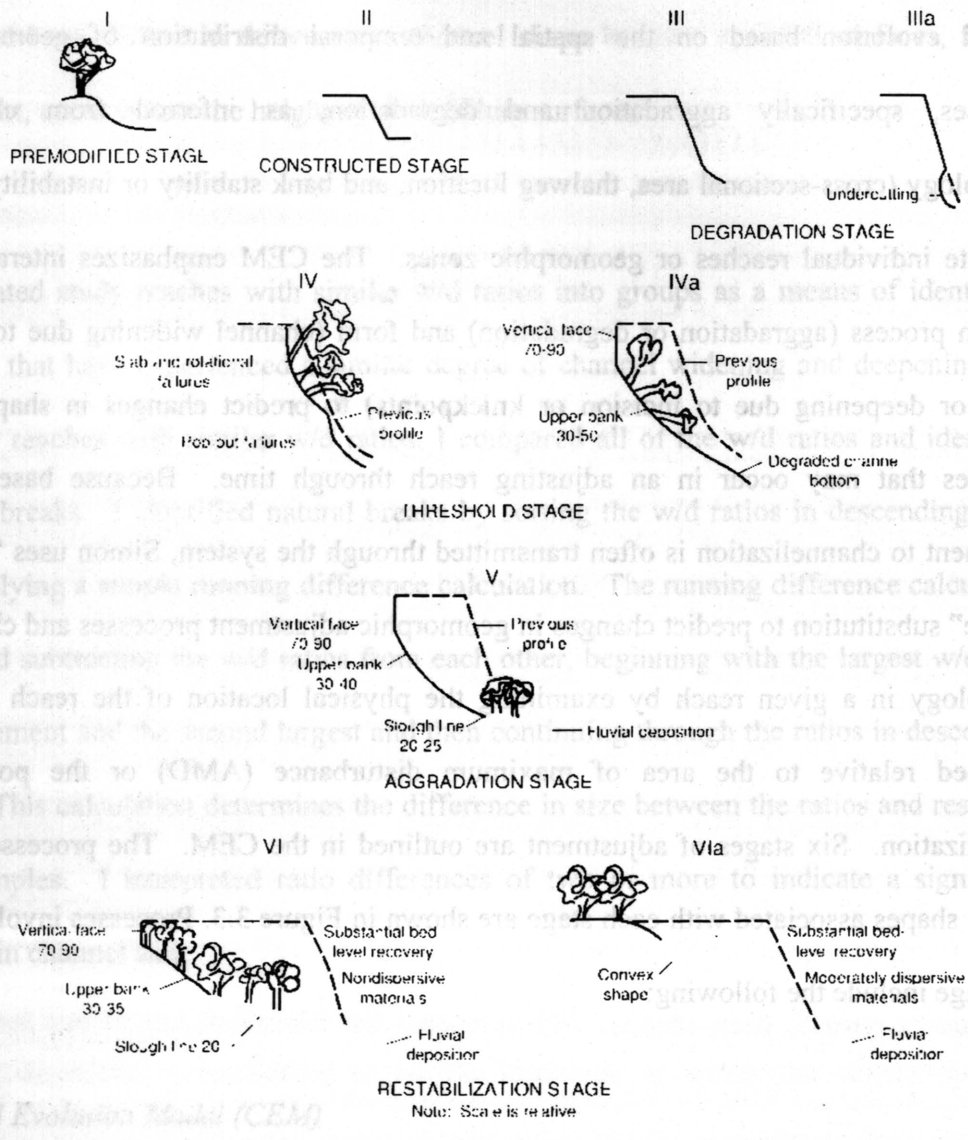

Figure 3.3: Six stages of Channel Evolution Model (Simon, 1994).

Stage IV: Threshold Stage - channel incision and bank undercutting cause the critical bank height to be exceeded; bank shape is controlled by mass wasting which facilitates bank retreat (channel widening);

Stage V: Aggradation Stage - sustained bank failures cause aggradation on the channel bed but reduced bank angle in development;

Stage VI: Restabilization Stage - bank heights greatly reduced due to substantial bed aggradation, and upper bank retreat halts.

All six stages of adjustment may not occur in any single reach. The model, however, does imply that base level adjustments that occur in response to channelization initiate a progressive series of bank failure processes and bank shapes during the adjustment process.

I applied the CEM to each study reach mainly by analyzing observations made in the field about bank shape and stability. Bank observations included presence or absence of bank failure, material composition of the bank (cohesive or non-cohesive), bank angle (upper, middle, and lower), and vegetation characteristics (presence or absence, degree of leaning in trees, relative age – mature or young). I also noted the type of bank failure (geotechnical – related to structural integrity of bank material or gravitational – related to basal undercutting and removal of basal support by flow) to identify the underlying cause of failure.

Results

I surveyed channel morphology in 34 reaches in the three study channels (Table 3.2). Average bankfull depth and bankfull width were greatest in Richland Creek. The watershed average for bankfull stage w/d ratio was the largest in Dry Creek. Richland Creek also had the largest average values for top-of-bank stage measurements of width, depth, and w/d ratio. Average sediment depth, average left/right bank angles, and average reach gradient were fairly similar among the three streams, with sediment depth ranging between 70 cm and 86 cm, bank angles between 56° and 70°, and a reach gradient of 0.003. Stream bank surveys showed that all reaches exhibited evidence of bank failure, either dormant or active, which mainly consisted of bench and slump failures related to bank undercutting.

Table 3.2: Average values of channel morphologic variables for the three study watersheds based on primary cross-section measurements.

Study Tributary	Qb_D (m)	Qb_W (m)	Qb W/D Ratio	Qb_ XA (sq m)	Qt_D (m)	Qt_W (m)	Qt _XA (sq m)	Qt W/D Ratio	SD (m)	LBA (deg)	RBA (deg)	RG
Dry	0.22	6.18	32.64	1.55	1.75	15.08	9.21	36.05	0.79	56.28	59.53	0.00063
Jeffers	0.52	5.14	12.64	2.79	1.71	12.37	29.35	21.22	0.70	57.90	60.43	0.00270
Richland	1.02	9.02	13.85	9.40	2.94	17.86	6.10	55.84	0.84	59.45	72.05	0.00130

Qb = bankfull stage; Qt = top of bank stage; D = depth; W= width; XA = cross-sectional area
SD = avg. sediment depth; LBA/RBA = left/right bank angle (upper, middle, lower); RG = reach gradient

In the following discussion of the results of channel morphology surveys and the CEM for each of the three study watersheds, unless otherwise stated, I compare and summarize measurements for reaches using only the characteristics of the primary cross-section. The primary cross-section was measured in the most detail. I also include channel morphology measurements for the two other cross-sections measured in each study reach in the tables to help summarize the channel morphology and CEM results generated for each study watershed.

Richland Creek

Cross-sectional morphology varied in Richland Creek (Table 3.3), but some reaches demonstrated similarity in shape, including reaches R2–R3 and reaches R6–R8. Top-of-bank depth increased from 1.72 m at reach R1 to 4.36 m at reach R4, then decreased to 2.24 m at reach R8. The smallest top-of-bank w/d ratio was 3.31 at reach R1. All other reaches exhibited top-of-bank w/d ratios ranging around 5 to 8. Bankfull depth increased from 1.40 m at reach R1 to 1.83 m at reach R4, and then decreased to 0.45 m at reach R8. Bankfull w/d ratios ranged from a minimum of 10.93 at reach R5 to a maximum of 30.67 at reach R6. The smallest bankfull w/d ratio was 3.56 at reach R1. Sediment depths at all reaches approached 1 m, with the exception of reach R1, which had a sediment depth of only 0.20 m. Bank angles for upper banks were all 90°, indicating vertical faces. Middle bank angles varied substantially between 42° and 90°. Lower bank angles also had a wide range with angles between 25° and 73°. In addition to the bank angle measurements, observations of bank processes I made in the field indicate that every

Table 3.3: Results of cross-sectional channel surveys for Richland Creek.

Study Reach	Qb_D (m)	Qb_W (m)	Qb W/D Ratio	Qb_ XA (sq m)	Qt_D (m)	Qt_W (m)	Qt W/D Ratio	Qt_XA (sq m)	SD (m)	LBA (deg)	RBA (deg)	RG
R1a	1.40	4.98	3.56	7.64	1.72	5.70	3.31	9.81	0.2	90	90	0.002
R1b	1.67	7.00	4.19	11.69						53	50	
R1c	1.83	8.30	4.54	15.19						45	50	
R2a	1.08	12.50	11.57	14.00	2.64	21.50	8.15	56.72	1	90	90	0.002
R2b	0.89	5.00	5.62	4.45						53	61	
R2c	0.80	7.30	9.13	5.83						27	55	
R3a	1.03	13.15	12.77	13.48	2.92	23.70	8.10	69.32	1	90	90	0.001
R3b	1.29	9.30	7.21	12.03						42	90	
R3c	1.37	9.80	7.15	13.41						27	70	
R4a	1.83	8.15	4.45	16.07	4.36	21.70	4.98	94.63	0.7	90	90	7E-06
R4b	0.86	6.20	7.21	5.33						45	90	
R4c	0.86	7.50	8.72	6.42						25	90	
R5a	1.51	16.50	10.93	25.02	3.75	21.20	5.65	79.50	1	90	90	6E-04
R5b	1.17	10.00	8.55	11.66						45	55	
R5c	1.21	9.40	7.77	11.34						38	35	
R6a	0.30	9.20	30.67	2.84	3.08	16.00	5.19	49.30	1	90	90	0.003
R6b	0.15	8.10	53.29	1.23						52	50	
R6c	0.35	6.70	19.14	2.33						52	50	
R7a	0.44	10.80	24.55	5.00	2.08	15.20	7.31	31.60	1	90	90	0.001
R7b	0.29	10.50	35.96	3.07						55	65	
R7c	0.40	8.80	22.22	3.48						35	73	
R8a	0.45	9.10	20.22	4.25	2.24	10.80	4.82	24.21	1	90	90	3E-04
R8b	0.35	9.60	27.43	3.36						60	60	
R8c	0.34	10.40	30.59	3.43						32	35	

a = primary cross-section; b = upstream cross-section; c = downstream cross-section

Qb = bankfull stage; Qt = top of bank stage; D = depth; W= width; XA = cross-sectional area

SD = avg. sediment depth; LBA/RBA = left/right bank angle (upper, middle, lower); RG = reach gradient

reach studied in Richland Creek exhibited evidence of either active or dormant bank failure. Figure 3.4 provides an example of active and dormant bank failure exhibited in cross-sectional shape and Table 3.4 summarizes bank failure processes in Richland Creek. Dormant bank failure was characterized by the presence of a slump or bench deposit of material similar to the upper bank that was protected from undercutting by an attached bar. Reach R8 exhibited evidence of dormant bank failure. Bank failure currently active consisted of slumps and bench failures induced by bank undercutting. In reach R3, the failures appeared to be related to the cohesiveness and shear strength of the bank material present because the failures in this reach consisted of cantilever and piping failure. Only three reaches exhibited similar bank profiles, indicated by similar bank angles, on both sides of the primary cross-section. These were reaches R5, R6, and R8 (Table 3.3).

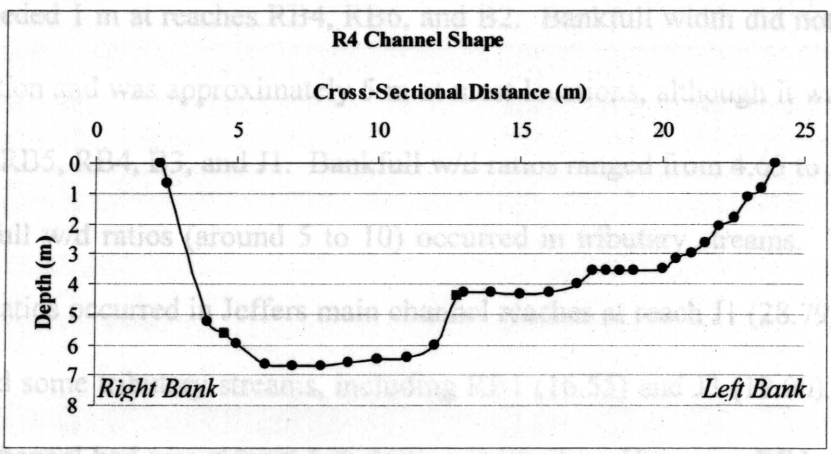

Figure 3.4: Example of active bank failure from undercutting on right bank and dormant bank failure with berm protection on left bank.

Table 3.4: Description of bank failures in Richland Creek.

Reach	Mode of Failure						Failure Location on Bank					Status
	Slump	Slab	Cantilever	Pop-Out	Piping	Dry Granular	Toe	Lower	Middle	Upper	Whole	Active or Dormant
R1												
left bank	X								X	X		ACTIVE
right bank	X								X	X		ACTIVE
R2												
left bank												
right bank		X							X	X		ACTIVE
R3												
left bank		X								X		DORMANT
right bank			X		X					X		ACTIVE
R4												
left bank	X									X		DORMANT
right bank	X										X	ACTIVE
R5												
left bank	X								X	X		ACTIVE
right bank												
R6												
left bank	X								X	X		ACTIVE
right bank	X									X		DORMANT
R7												
left bank												DORMANT
right bank	X										X	ACTIVE
R8												
left bank	X									X		DORMANT
right bank	X									X		DORMANT

Jeffers Creek

Jeffers Creek is composed of three sub-watersheds — Jeffers Creek main channel and minor tributaries that join in the lower half of the watershed (J); Brown's Creek, a major tributary to the main channel (B); and Rice Branch, the other major tributary to the main channel (RB).

Cross-sectional channel morphology in Jeffers Creek was fairly consistent between the reaches surveyed (Tables 3.5a, 3.5b, and 3.5c). Top-of-bank depth was around 2 m at all reaches surveyed. Top-of-bank width was greater than 9 m at all reaches, with tributary streams having smaller top-of-bank widths than Jeffers main channel reaches. The largest top-of-bank widths occurred in J1, J3, and J5 and were all greater than 18 m. Top-of-bank w/d ratio was large for all reaches with the exception of J2 (13.09) and B1 (12.50). In Brown's Creek, top-of-bank w/d ratio was around 17, while Rice Branch ranged from approximately 18 to 27.85. In most cases, bankfull depth was around 0.60 m, but it exceeded 1 m at reaches RB4, RB6, and B2. Bankfull width did not exceed 10 m at any location and was approximately 5 m at most locations, although it was nearer to 10 m at RB6, RB5, RB4, B3, and J1. Bankfull w/d ratios ranged from 4.63 to 28.70. The smaller bankfull w/d ratios (around 5 to 10) occurred in tributary streams. The largest bankfull w/d ratios occurred in Jeffers main channel reaches at reach J1 (28.79) and reach J5 (17.15), and some tributary streams, including RB1 (16.55) and J3 (19.00). Sediment stored in the channel bed was at least 1 m deep at most sites. However, RB1, RB2, RB3, RB4, RB6, and B1 all had sediment depths between 0.11 m and 0.68 m.

Table 3.5: Results of cross-sectional channel surveys for Jeffers Creek.

a. Jeffers Creek, main channel and minor tributaries.

Study Reach	Qb_D (m)	Qb_W (m)	Qb W/D Ratio	Qb_ XA (sq m)	Qt_D (m)	Qt_W (m)	Qt _XA (sq m)	Qt W/D Ratio	SD (m)	LBA (deg)	RBA (deg)	RG
J1a	0.29	8.35	28.79	2.21	1.99	19.28	52.27	38.37	1.00	90	90	0.002
J1b	0.24	8.36	34.83	2.01						58	44	
J1c	0.39	8.00	20.51	3.12						13	25	
J2a	0.33	2.98	9.03	1.01	1.19	11.00	16.65	13.09	1.00	90	90	0.002
J2b	0.25	2.30	9.20	0.58						46	48	
J2c	0.17	2.40	14.12	0.41						32	77	
J3a	0.30	5.70	19.00	1.60	1.72	18.00	34.79	30.96	1.00	90	90	0.003
J3b	0.14	3.50	25.00	0.49						50	29	
J3c	0.34	5.10	15.00	1.73						46	24	
J5a	0.26	4.46	17.15	1.19	1.72	19.22	39.76	33.06	1.00	90	90	0.001
J5b	0.49	8.00	16.33	3.92						37	29	
J5c	0.39	3.50	8.97	1.37						40	17	

a = primary cross-section; b = upstream cross-section; c = downstream cross-section
Qb = bankfull stage; Qt = top of bank stage; D = depth; W= width; XA = cross-sectional area
SD = avg. sediment depth; LBA/RBA = left/right bank angle (upper, middle, lower); RG = reach gradient

Table 3.5: Continued.

b. Brown's Creek, tributary to Jeffers Creek.

Study Reach	Qb_D (m)	Qb_W (m)	Qb W/D Ratio	Qb_ XA (sq m)	Qt_D (m)	Qt_W (m)	Qt _XA (sq m)	Qt W/D Ratio	SD (m)	LBA (deg)	RBA (deg)	RG
B1a	0.33	4.85	14.70	1.26	1.25	10.00	15.67	12.50	0.45	90	90	0.001
B1b	0.64	4.40	6.88	2.82						56	58	
B1c	0.56	5.10	9.11	2.86						49	41	
B2a	0.82	3.80	4.63	2.69	2.25	7.71	22.10	17.35	1.00	90	90	0.001
B2b	1.03	1.80	1.75	1.85						71	52	
B2c	1.10	2.40	2.18	2.64						65	22	
B3a	0.61	8.17	13.39	4.55	1.50	11.30	23.82	16.95	no sample	30	90	0.007
B3b	0.48	5.05	10.52	2.42						48	90	
B3c	0.95	5.83	6.14	5.54						35	90	
B4a	0.45	4.49	9.98	1.59	1.84	9.30	31.51	17.11	1.00	90	90	0.003
B4b	0.68	5.20	7.65	3.54						58	57	
B4c	0.52	4.30	8.27	2.24						40	13	

a = primary cross-section; b = upstream cross-section; c = downstream cross-section
Qb = bankfull stage; Qt = top of bank stage; D = depth; W= width; XA = cross-sectional area
SD = avg. sediment depth; LBA/RBA = left/right bank angle (upper, middle, lower); RG = reach gradient

Table 3.5: Continued.

c. Rice Branch, tributary to Jeffers Creek.

Study Reach	Qb_D (m)	Qb_W (m)	Qb W/D Ratio	Qb_ XA (sq m)	Qt_D (m)	Qt_W (m)	Qt _XA (sq m)	Qt W/D Ratio	SD (m)	LBA (deg)	RBA (deg)	RG
RB1a	0.31	5.13	16.55	1.12	1.53	11.71	24.35	17.92	0.21	90	90	0.003
RB1b	0.47	5.30	11.28	2.49						37	30	
RB1c	0.25	6.10	24.40	1.53						59	26	
RB2a	0.45	4.72	10.49	2.04	1.96	14.21	36.26	27.85	0.11	90	90	0.001
RB2b	0.40	3.40	8.50	1.36						39	70	
RB2c	0.49	5.00	10.20	2.45						21	60	
RB3a	0.33	4.40	13.33	1.42	1.77	10.90	24.37	19.29	0.33	90	90	0.000
RB3b	0.24	3.10	12.92	0.74						54	34	
RB3c	0.27	2.50	9.26	0.68						29	29	
RB4a	1.76	9.91	5.63	18.50	1.61	11.17	29.93	17.98	0.68	90	90	0.002
RB4b	0.22	5.00	22.73	1.10						45	60	
RB4c	0.38	5.50	14.47	2.09						69	45	
RB5a	0.56	7.30	13.04	4.20	1.99	10.20	38.73	20.30	1.00	90	90	0.000
RB5b	0.57	8.90	15.61	5.07						40	40	
RB5c	0.54	7.90	14.63	4.27						30	90	
RB6a	1.09	7.18	6.59	8.45	1.56	9.16	20.62	14.29	0.38	90	90	0.010
RB6b	0.61	3.80	6.23	2.32						41	50	
RB6c	1.33	2.80	2.11	3.72						24	28	

a = primary cross-section; b = upstream cross-section; c = downstream cross-section

Qb = bankfull stage; Qt = top of bank stage; D = depth; W= width; XA = cross-sectional area

SD = avg. sediment depth; LBA/RBA = left/right bank angle (upper, middle, lower); RG = reach gradient

Bank angles for upper banks were all 90°, indicating vertical faces. Middle bank angles varied substantially between 29° and 71°, as did lower bank angles, which ranged from 13° to 77°. Field observations of bank conditions indicate that all reaches surveyed had evidence of dormant or active bank failure (Table 3.6). Most bank failures were either slumps or bench failures that appeared to occur because of bank undercutting. Reaches J2, J3, and RB6 all exhibited extensive bench failures, 1–2 m in thickness and 5–10 m in length. Mass failure in reaches B2, B3, RB1, and RB2 appeared to be related to structural properties of the bank material, such as cohesiveness and shear strength, because mass failure processes in these reaches included pop-out and/or piping processes.

Most cross-sections have asymmetric channel shapes as a consequence of bank failure processes (Figures 3.5, 3.6, and 3.7). Only J1, B1, and RB6 have similar bank shapes on both sides of the same cross-section, as indicated by similar bank angles on both sides of the cross-section (Table 3.5).

Dry Creek

Variations in cross-sectional channel morphologic characteristics in Dry Creek mainly involve variables of width (Table 3.7). Top-of-bank depth was approximately 2 m at most reaches. Top-of-bank depth was substantially smaller at D4 (0.55 m) and D8 (1.07 m) and larger at D2 (3.16 m). Top-of-bank width ranged between 10 m and 14 m at most sites, except at D5 (24.10 m), D7 (19.00 m), and D11 (31.50). Top-of-bank w/d ratio was between 7.29 and 10.56 at most reaches. The w/d ratio was larger at D4 (13.91), D5 (13.24), and D11 (15.75) and smaller at D1 (4.77) and D2 (4.24). Bankfull depth ranges

Table 3.6: Description of bank failures in Jeffers Creek.

Reach	Mode of Failure						Failure Location on Bank					Status
	Slump	Slab	Cantilever	Pop-Out	Piping	Dry Granular	Toe	Lower	Middle	Upper	Whole	Active or Dormant
B1												
left bank	X								X	X		ACTIVE
right bank	X									X		DORMANT
B2												
left bank				X							X	ACTIVE
right bank		X								X		DORMANT
B3												
left bank		X								X		DORMANT
right bank		X		X					X	X		ACTIVE
B4												
left bank	X									X		DORMANT
right bank		X								X		ACTIVE
RB1												
left bank				X	X					X		ACTIVE
right bank		X								X		DORMANT
RB2												
left bank			X		X					X		ACTIVE
right bank		X								X		DORMANT
RB3												
left bank		X								X		DORMANT
right bank	X										X	ACTIVE
RB4												
left bank	X									X		ACTIVE
right bank	X										X	ACTIVE
RB5												
left bank	X									X		DORMANT
right bank	X									X		ACTIVE
RB6												
left bank	X									X		DORMANT
right bank		X								X		ACTIVE
J1												
left bank	X									X		DORMANT
right bank	X									X		DORMANT
J2												
left bank		X								X		DORMANT
right bank		X								X		ACTIVE
J3												
left bank		X								X		DORMANT
right bank		X								X		DORMANT
J5												
left bank	X									X		ACTIVE
right bank	X									X		ACTIVE

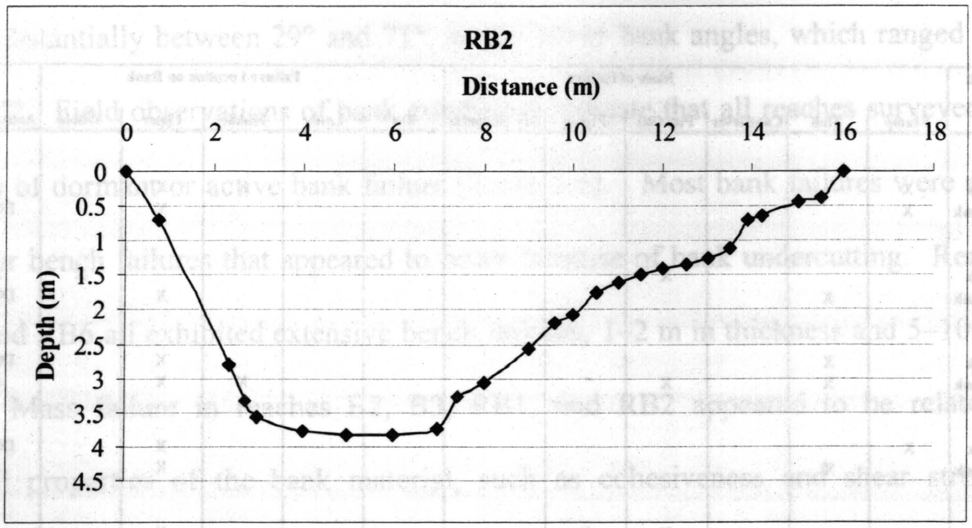

Figure 3.5: Example of asymmetric channel shape caused by bank failure in Rice Branch, Jeffers Creek.

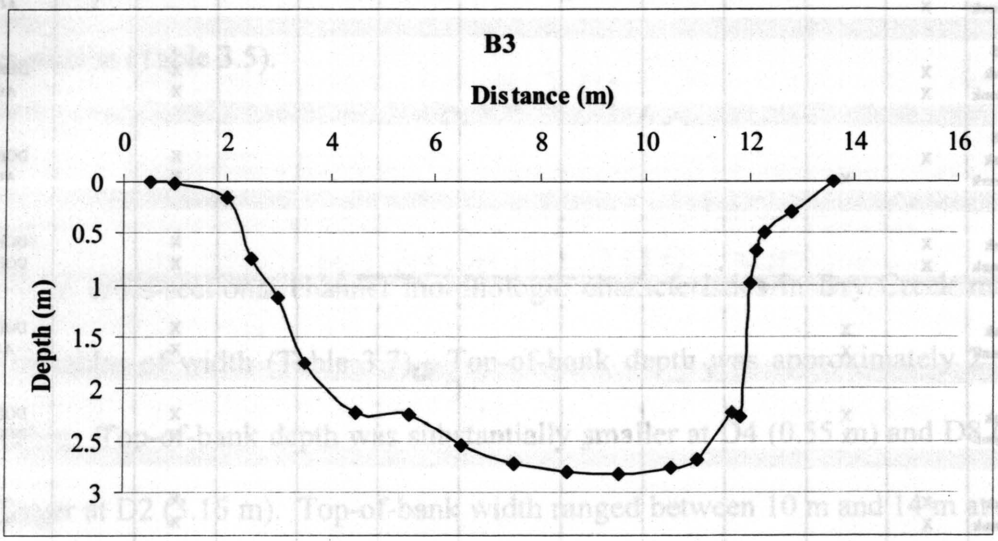

Figure 3.6: Example of asymmetric channel shape caused by bank failure in Browns Creek, Jeffers Creek.

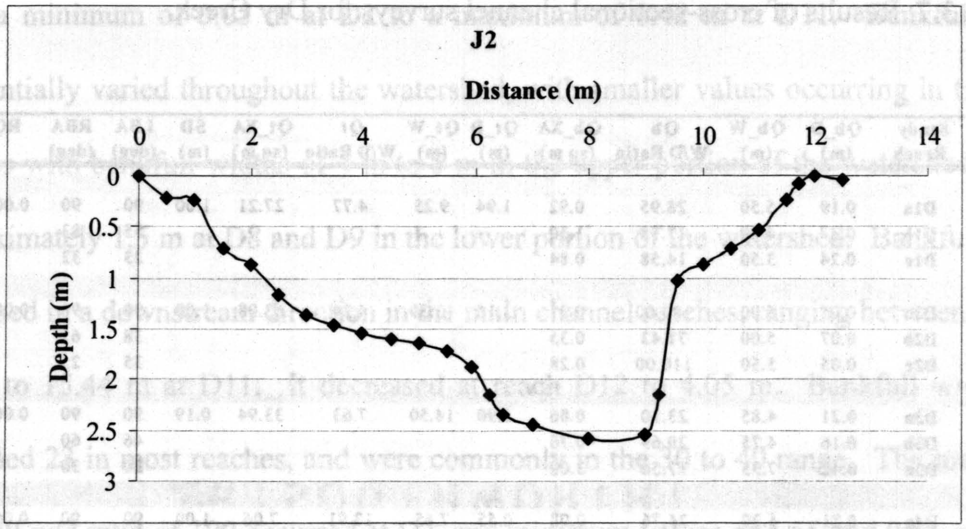

Figure 3.7: Example of asymmetric channel shape caused by bank failure in Jeffers main channel.

Table 3.7: Results of cross-sectional channel surveys for Dry Creek.

Study Reach	Qb_D (m)	Qb_W (m)	Qb W/D Ratio	Qb_XA (sq m)	Qt_D (m)	Qt_W (m)	Qt W/D Ratio	Qt_XA (sq m)	SD (m)	LBA (deg)	RBA (deg)	RG
D1a	0.19	5.50	28.95	0.92	1.94	9.25	4.77	27.21	1.00	90	90	0.000
D1b	0.27	4.80	17.78	1.30						55	83	
D1c	0.24	3.50	14.58	0.84						23	32	
D2a	0.05	5.00	100.00	0.21	3.16	13.39	4.24	63.08	1.00	90	90	0.000
D2b	0.07	5.00	71.43	0.35						38	61	
D2c	0.05	5.50	110.00	0.28						35	25	
D3a	0.21	4.85	23.10	0.86	1.90	14.50	7.63	33.94	0.19	90	90	0.004
D3b	0.16	4.75	29.69	0.76						46	60	
D3c	0.42	7.35	17.50	3.09						20	30	
D4a	0.21	5.20	24.76	0.98	0.55	7.65	13.91	7.06	1.00	90	90	0.000
D4b	0.27	6.20	22.96	1.67						45	46	
D4c	0.27	5.40	20.00	1.46						25	41	
D5a	0.21	7.72	36.76	1.55	1.82	24.10	13.24	54.47	0.44	90	90	0.000
D5b	0.22	12.60	57.27	2.77						51	50	
D5c	0.20	13.80	69.00	2.76						49	33	
D6a	0.22	3.93	17.86	0.81	1.68	12.37	7.36	27.93	1.00	90	90	0.000
D6b	0.32	6.76	21.13	2.16						65	30	
D6c	0.31	5.11	16.48	1.58						29	14	
D7a	0.16	6.80	42.50	1.07	2.28	19.00	8.33	56.11	0.42	90	90	0.000
D7b	0.19	5.50	28.95	1.05						34	40	
D7c	0.19	7.70	40.53	1.46						25	60	
D8a	0.17	1.13	6.65	0.19	1.07	11.30	10.56	14.02	0.46	90	90	0.000
D8b	0.20	1.75	8.75	0.35						29	35	
D8c	0.18	2.45	13.61	0.44						21	52	
D9a	0.18	1.73	9.61	0.18	1.44	10.50	7.29	19.62	1.00	90	90	0.001
D9b	0.12	2.20	18.33	0.26						36	50	
D9c	0.14	1.10	7.86	0.15						26	48	
D10a	0.27	9.83	36.41	2.41	1.57	14.20	9.04	30.06	1.00	90	90	0.001
D10b	0.17	11.00	64.71	1.87						58	53	
D10c	0.22	11.20	50.91	2.46						61	44	
D11a	0.42	15.44	36.76	6.57	2.00	31.50	15.75	74.06	1.00	90	90	0.000
D11b	0.55	10.50	19.09	5.78						65	46	
D11c	0.51	11.00	21.57	5.61						60	20	
D12a	0.25	4.05	16.20	1.03	1.58	13.24	8.38	25.06	1.00	90	90	0.000
D12b	0.13	2.10	16.15	0.27						35	60	
D12c	0.11	4.10	37.27	0.45						15	50	

a = primary cross-section; b = upstream cross-section; c = downstream cross-section
Qb = bankfull stage; Qt = top of bank stage; D = depth; W= width; XA = cross-sectional area
SD = avg. sediment depth; LBA/RBA = left/right bank angle (upper, middle, lower); RG = reach gradient

from a minimum of 0.05 m at D2 to a maximum of 0.42 m at D11. Bankfull width substantially varied throughout the watershed, with smaller values occurring in tributary reaches with bankfull widths of 4 m to 5 m in the upper portion of the watershed and of approximately 1.5 m at D8 and D9 in the lower portion of the watershed. Bankfull width increased in a downstream direction in the main channel reaches, ranging between 7.72 m at D5 to 15.44 m at D11. It decreased at reach D12 to 4.05 m. Bankfull w/d ratios exceeded 23 in most reaches, and were commonly in the 30 to 40 range. The maximum bankfull w/d ratio of 100 occurred at D2, and minimum values of 6.65 and 9.61 occurred in D8 and D9, respectively. Sediment depth was approximately 0.50 m at D3, D5, D7, and D8 and at least 1 m at all other locations. My observations of bank processes indicated an abundance of recent, catastrophic mass failure in Dry Creek. All upper banks were vertical, having a bank angle of 90°. Middle bank angles ranged between 29° and 83°. Lower bank angles ranged from 14° to 60°. All the reaches surveyed exhibited evidence of bank failure, either active or dormant (Table 3.8). Slumps and bench failures were the most common type of failure and appeared to be induced by bank undercutting. Piping and bank failure in reaches D2 and D9 are most likely related to bank material cohesion and shear strength. In Dry Creek, bench failures were large in size and often exceeded 20 m in length and 2 m in thickness. Based on my field observations, Dry Creek exhibited the most severe state of bank instability of the three study watersheds in terms of the frequency and magnitude of bank failures. Like most reaches in Richland and Jeffers Creeks, most reaches in Dry Creek had one bank with active bank failure and one bank with dormant bank failure (bench or slump protected by attached sand bar) (Figure 3.8). Reaches D2, D5, and D10 had active failures on both banks (Figure 3.9).

Table 3.8: Description of bank failures in Dry Creek.

Reach	Mode of Failure						Failure Location on Bank					Status
	Slump	Slab	Cantilever	Pop-Out	Piping	Dry Granular	Toe	Lower	Middle	Upper	Whole	Active or Dormant
D1												
left bank		X								X		DORMANT
right bank		X								X		ACTIVE
D2												
left bank	X									X		ACTIVE
right bank		X			X					X		ACTIVE
D3												
left bank	X									X		DORMANT
right bank	X									X		ACTIVE
D4												
left bank		X								X		DORMANT
right bank		X										ACTIVE
D5												
left bank												
right bank	X									X		ACTIVE
D6												
left bank	X										X	ACTIVE
right bank	X									X		DORMANT
D7												
left bank		X								X		DORMANT
right bank		X								X		ACTIVE
D8												
left bank		X								X		DORMANT
right bank		X								X		ACTIVE
D9												
left bank		X								X		DORMANT
right bank	X				X					X		ACTIVE
D10												
left bank	X								X	X		ACTIVE
right bank	X									X		ACTIVE
D11												
left bank	X	X							X	X		ACTIVE
right bank		X								X		DORMANT
D12												
left bank	X	X								X		DORMANT
right bank	X									X		ACTIVE

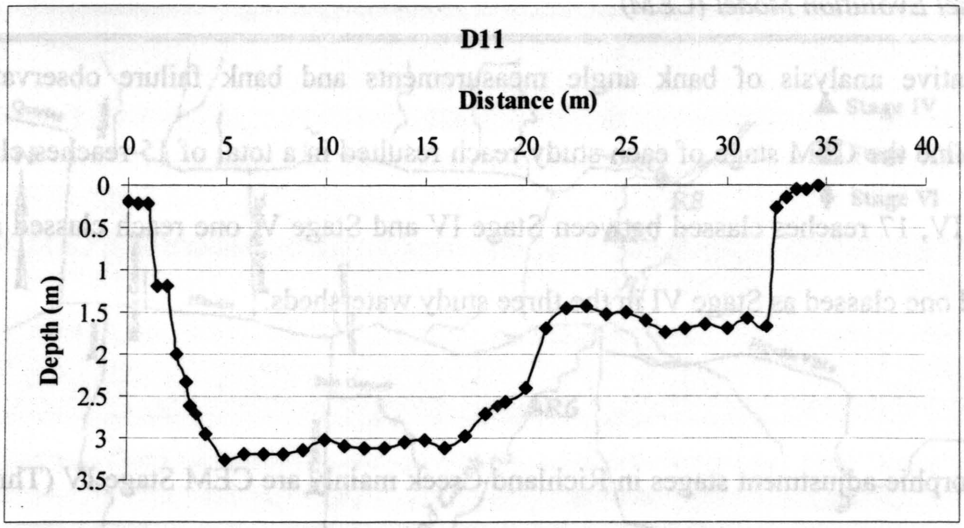

Figure 3.8: Example of asymmetric channel shape caused by active and dormant bank failure in Dry Creek.

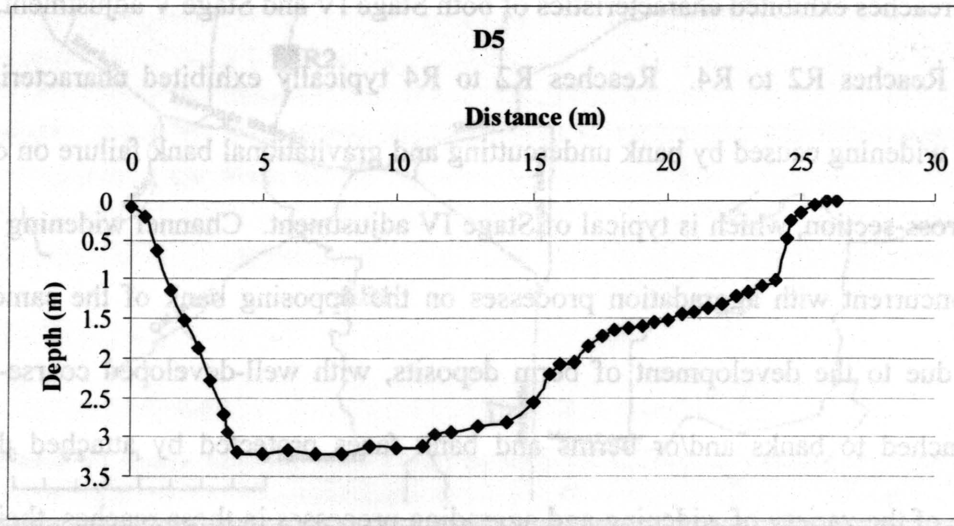

Figure 3.9: Example of channel shape caused by bank failure active on both banks in Dry Creek.

Channel Evolution Model (CEM)

Qualitative analysis of bank angle measurements and bank failure observations to determine the CEM stage of each study reach resulted in a total of 15 reaches classed as Stage IV, 17 reaches classed between Stage IV and Stage V, one reach classed as Stage V, and one classed as Stage VI in the three study watersheds.

Geomorphic adjustment stages in Richland Creek mainly are CEM Stage IV (Threshold), Stage V (Aggradation), and one Stage VI (Re-stabilized) (Figure 3.10). Reaches R1, R5, R6, and R7 exhibited Stage IV adjustment, having relatively steep middle and lower-slope bank angles that are the product of active channel widening related to bank failure. Reach R8 had characteristics of Stage VI adjustment, with gentle lower bank slopes, relative channel symmetry, and no field evidence of active bank failure processes. Several reaches exhibited characteristics of both Stage IV and Stage V adjustment. These include Reaches R2 to R4. Reaches R2 to R4 typically exhibited characteristics of channel widening caused by bank undercutting and gravitational bank failure on one side of the cross-section, which is typical of Stage IV adjustment. Channel widening process were concurrent with aggradation processes on the opposing bank of the same cross-section due to the development of berm deposits, with well-developed coarse-grained bars attached to banks and/or berms and bank faces protected by attached deposits. Because of the variety of widening and aggrading processes in these reaches, their cross-sectional shapes are generally quite asymmetrical, and they can have large w/d ratios.

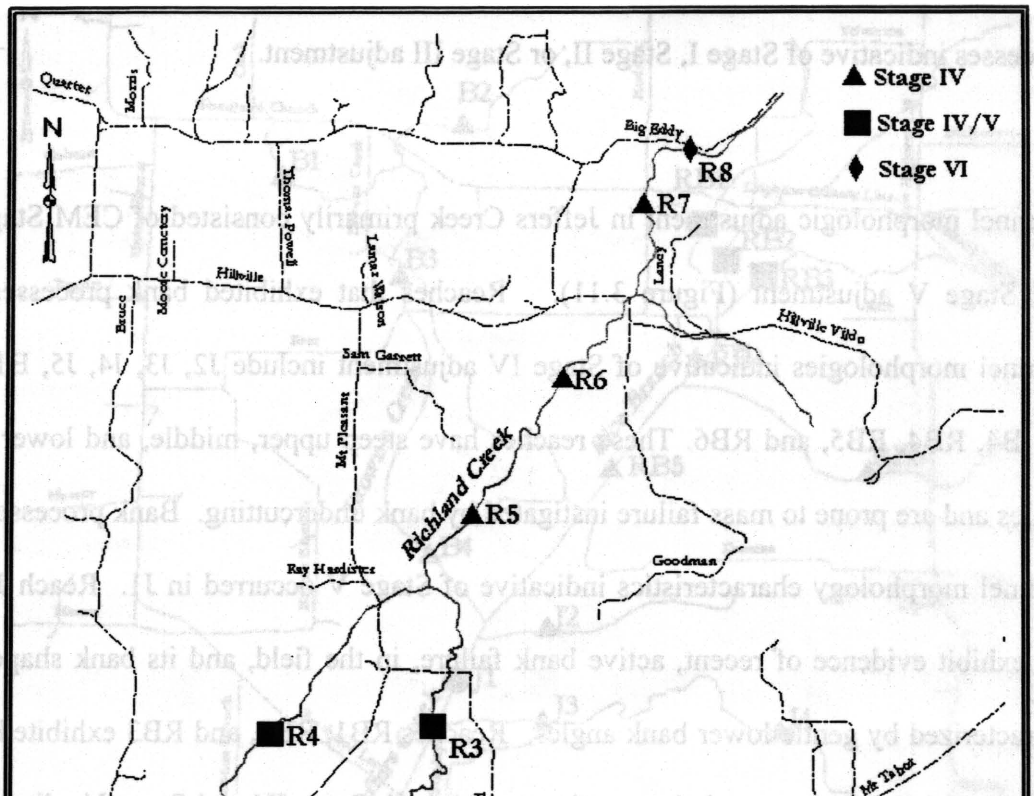

Figure 3.10: Spatial distribution of CEM stages in Richland Creek.

None of the reaches surveyed exhibited channel morphologic characteristics or bank processes indicative of Stage I, Stage II, or Stage III adjustment.

Channel morphologic adjustment in Jeffers Creek primarily consisted of CEM Stage IV and Stage V adjustment (Figure 3.11). Reaches that exhibited bank processes and channel morphologies indicative of Stage IV adjustment include J2, J3, J4, J5, B1, B2, B3, B4, RB4, RB5, and RB6. These reaches have steep upper, middle, and lower bank angles and are prone to mass failure instigated by bank undercutting. Bank processes and channel morphology characteristics indicative of Stage V occurred in J1. Reach J1 did not exhibit evidence of recent, active bank failure, in the field, and its bank shapes are characterized by gentle lower bank angles. Reaches RB1, RB2, and RB3 exhibited bank and channel shape characteristics consistent with both Stage IV and Stage V adjustment. In these reaches, one side of the cross-section has a steep bank face caused by bank failure and the opposing side of the same cross-section has a bank with gentler middle and lower bank slopes composed of berm deposits attached to the bank. None of the reaches surveyed in Jeffers Creek exhibited channel shape or bank processes consistent with Stage I, Stage II, or Stage III of adjustment processes.

Geomorphic adjustment processes evident in Dry Creek include Stage IV and Stage V adjustment (Figure 3.12). Two reaches (D5 and D10) exhibited Stage IV adjustment, having steep lower bank angles that indicate bank undercutting caused bank failure and

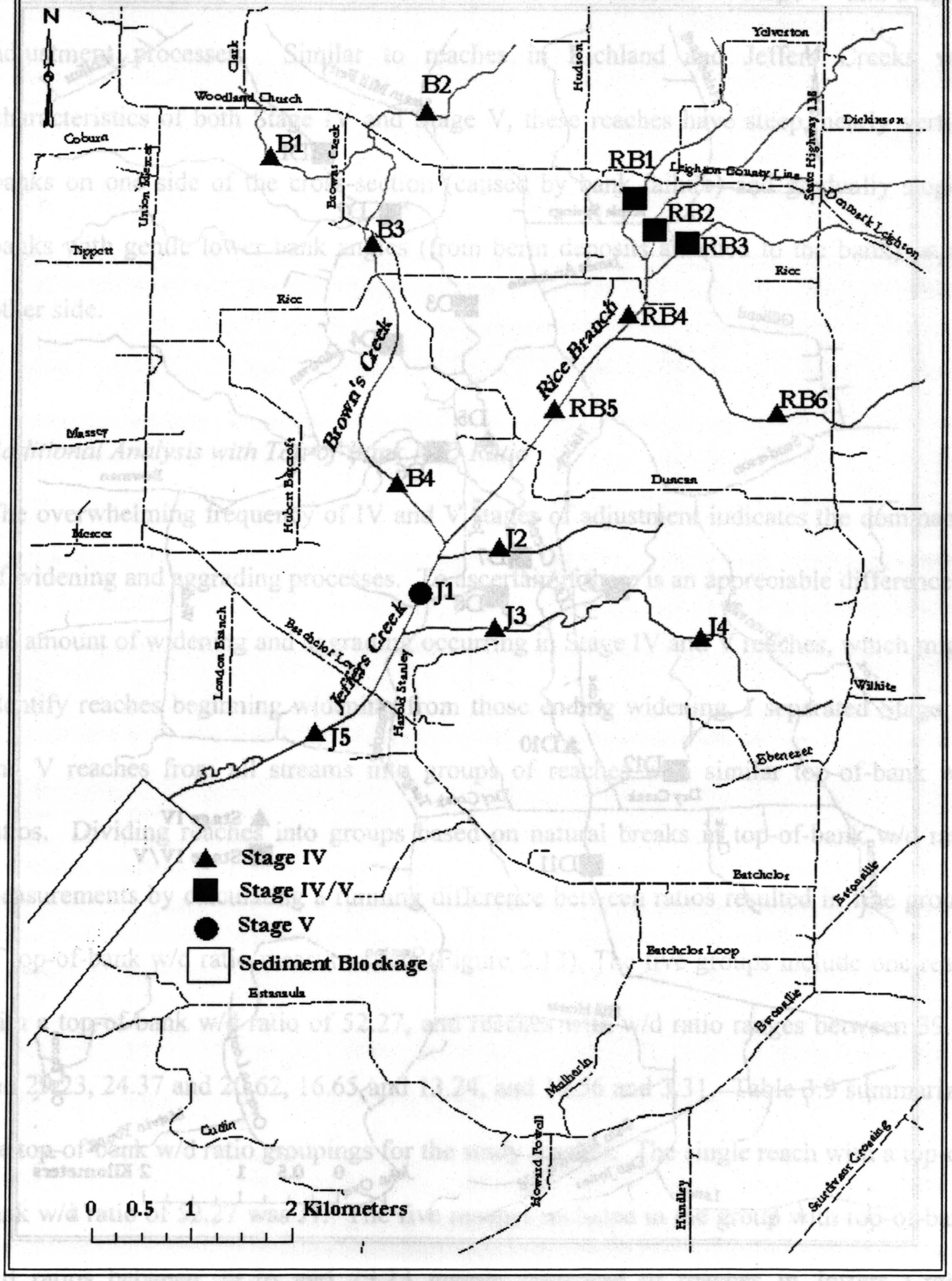

Figure 3.11: Spatial distribution of CEM stages in Jeffers Creek.

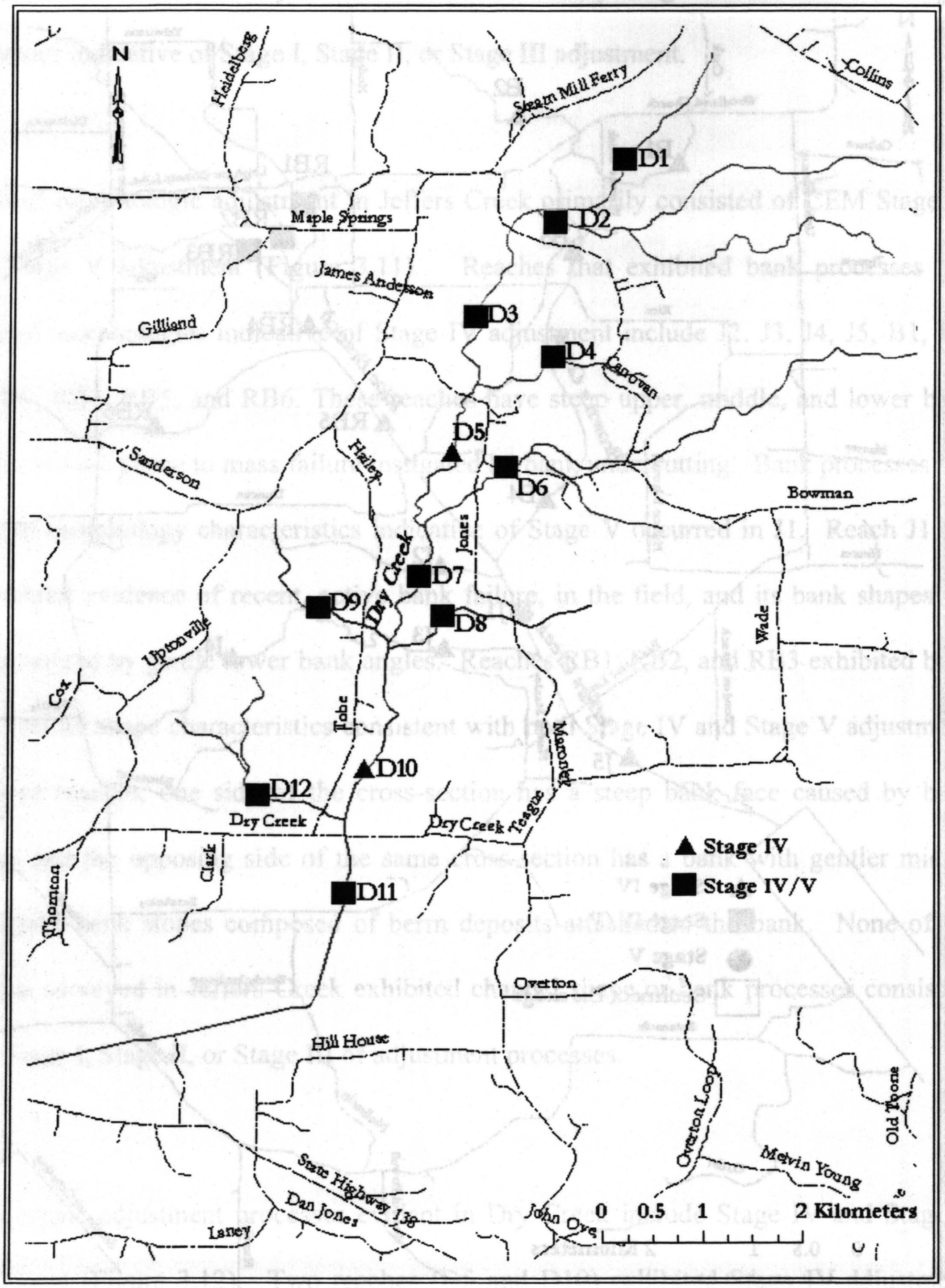

Figure 3.12: Spatial distribution of CEM stages in Dry Creek.

widened the channel. All other reaches exhibited a combination of Stage IV and Stage V adjustment processes. Similar to reaches in Richland and Jeffers Creeks with characteristics of both Stage IV and Stage V, these reaches have steep, nearly vertical banks on one side of the cross-section (caused by bank failure) and gradually sloping banks with gentle lower bank angles (from berm deposits attached to the bank) on the other side.

Additional Analysis with Top-of-Bank W/D Ratio

The overwhelming frequency of IV and V stages of adjustment indicates the dominance of widening and aggrading processes. To ascertain if there is an appreciable difference in the amount of widening and aggrading occurring in Stage IV and V reaches, which might identify reaches beginning widening from those ending widening, I separated Stage IV and V reaches from all streams into groups of reaches with similar top-of-bank w/d ratios. Dividing reaches into groups based on natural breaks in top-of-bank w/d ratio measurements by calculating a running difference between ratios resulted in five groups of top-of-bank w/d ratio measurements (Figure 3.13). The five groups include one reach with a top-of-bank w/d ratio of 52.27, and reaches with w/d ratio ranges between 39.76 and 29.23, 24.37 and 20.62, 16.65 and 13.24, and 10.56 and 3.31. Table 3.9 summarizes the top-of-bank w/d ratio groupings for the study reaches. The single reach with a top-of-bank w/d ratio of 52.27 was J1. The five reaches included in the group with top-of-bank w/d ratios between 39.76 and 29.23 mainly consisted of reaches in Jeffers Creek, including J5, RB5, RB2, J3, B4, and RB4. The four reaches with top-of-bank w/d ratios

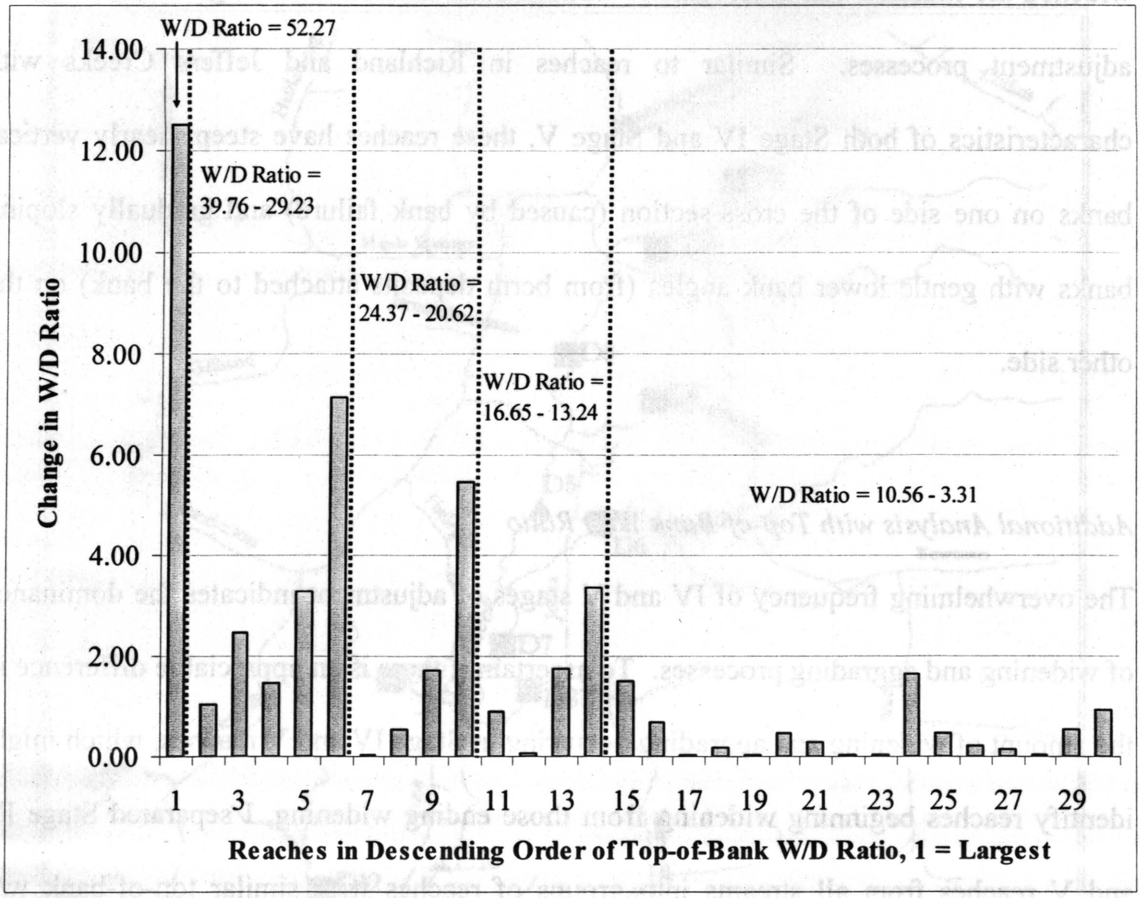

Figure 3.13: Breaks in top-of-bank w/d ratio measurements for all watersheds using running difference method with n = 35 and n–1 samples.

Table 3.9: Study reaches grouped by top-of-bank w/d ratio range.

Study Reach	Qb_D (m)	Qb_W (m)	Qb W/D Ratio	Qb_XA (sq m)	Qt_D (m)	Qt_W (m)	Qt W/D Ratio	Qt_XA (sq m)
J1a	0.29	8.35	28.79	2.21	1.99	19.28	52.27	38.37
J5a	0.26	4.46	17.15	1.19	1.72	19.22	39.76	33.06
RB5a	0.56	7.30	13.04	4.20	1.99	10.20	38.73	20.30
RB2a	0.45	4.72	10.49	2.04	1.96	14.21	36.26	27.85
J3a	0.30	5.70	19.00	1.60	1.72	18.00	34.79	30.96
B4a	0.45	4.49	9.98	1.59	1.84	9.30	31.51	17.11
RB4a	1.76	9.91	5.63	18.50	1.61	11.17	29.93	17.98
Average	**0.63**	**6.10**	**12.55**	**4.85**	**1.81**	**13.68**	**35.16**	**24.54**
RB3a	0.33	4.40	13.33	1.42	1.77	10.90	24.37	19.29
RB1a	0.31	5.13	16.55	1.12	1.53	11.71	24.35	17.92
B3a	0.61	8.17	13.39	4.55	1.50	11.30	23.82	16.95
B2a	0.82	3.80	4.63	2.69	2.25	7.71	22.10	17.35
RB6a	1.09	7.18	6.59	8.45	1.56	9.16	20.62	14.29
Average	**0.63**	**5.74**	**10.90**	**3.65**	**1.72**	**10.16**	**23.05**	**17.16**
J2a	0.33	2.98	9.03	1.01	1.19	11.00	16.65	13.09
D11a	0.42	15.44	36.76	6.57	2.00	31.50	15.75	74.06
B1a	0.33	4.85	14.70	1.26	1.25	10.00	15.67	12.50
D4a	0.21	5.20	24.76	0.98	0.55	7.65	13.91	7.06
D5a	0.21	7.72	36.76	1.55	1.82	24.10	13.24	54.47
Average	**0.30**	**7.24**	**24.40**	**2.27**	**1.36**	**16.85**	**15.04**	**32.24**
D8a	0.17	1.13	6.65	0.19	1.07	11.30	10.56	14.02
D10a	0.27	9.83	36.41	2.41	1.57	14.20	9.04	30.06
D12a	0.25	4.05	16.20	1.03	1.58	13.24	8.38	25.06
D7a	0.16	6.80	42.50	1.07	2.28	19.00	8.33	56.11
R2a	1.08	12.50	11.57	14.00	2.64	21.50	8.15	56.72
R3a	1.03	13.15	12.77	13.48	2.92	23.70	8.10	69.32
D3a	0.21	4.85	23.10	0.86	1.90	14.50	7.63	33.94
D6a	0.22	3.93	17.86	0.81	1.68	12.37	7.36	27.93
R7a	0.44	10.80	24.55	5.00	2.08	15.20	7.31	31.60
D9a	0.18	1.73	9.61	0.18	1.44	10.50	7.29	19.62
R5a	1.51	16.50	10.93	25.02	3.75	21.20	5.65	79.50
R6a	0.30	9.20	30.67	2.84	3.08	16.00	5.19	49.30
R4a	1.83	8.15	4.45	16.07	4.36	21.70	4.98	94.63
R8a	0.45	9.10	20.22	4.25	2.24	10.80	4.82	24.21
D1a	0.19	5.50	28.95	0.92	1.94	9.25	4.77	27.21
D2a	0.05	5.00	100.00	0.21	3.16	13.39	4.24	63.08
R1a	1.40	4.98	3.56	7.64	1.72	5.70	3.31	9.81
Average	**0.57**	**7.48**	**23.53**	**5.65**	**2.32**	**14.91**	**6.77**	**41.89**

between 24.37 and 20.62 were RB3, RB1, B3, B2, and RB6, all from Jeffers Creek and its tributaries. Of the four reaches with top-of-bank w/d ratios between 16.65 and 13.24, J2 and B1 were in Jeffers Creek and D11, D4, and D5 in Dry Creek. The sixteen reaches from Dry and Richland Creeks with top-of-bank w/d ratios between 10.56 and 3.31 were D1, D2, D3, D6, D7, D8, D10, and D9 in Dry Creek, and R1, R2, R3, R4, R5, R6, R7, and R8 in Richland Creek.

Discussion

In this study, I used measurements of channel shape, bank descriptions, and process observations I made in the field to identify the connections between geomorphic adjustment processes operating at different spatial and temporal scales and the ways in which these connections may translate into system-wide response. In addition, I also examined the applicability of a conceptual model of geomorphic adjustment for use in tributary streams with a history of multiple periods of disturbance.

Post-Channelization Channel Morphology

Some of the study tributaries have more consistency in their channel shape than others. Of the three tributaries analyzed, Jeffers Creek exhibited the least variability in channel depth and width between survey reaches. In both Richland Creek and Dry Creek, channel depth did not vary greatly but channel width changed considerably between survey locations.

Greater spatial variability of channel width in Richland and Dry Creeks may be caused by greater frequency and magnitude of bank failures related to greater vertical incision and lack of bank material cohesiveness. The average bankfull and top-of-bank depths for Richland Creek (1.02 m and 2.94 m, respectively) were deeper than for the other two tributaries. This may indicate that Richland Creek has incised to a greater extent than the other study tributaries. There are many possible explanations for more vertical incision to have occurred in Richland Creek, including: 1) the depth of unconsolidated alluvium may be greater than in the other study tributaries, which provides less resistance to incision, 2) the bed slope in Richland Creek was modified to a greater extent than in the other study tributaries, 3) the vertical incision in Richland Creek may have been taking place for a longer period of time because channelization work may have taken place in Richland Creek before the other study tributaries, and 4) some combination of the previous three explanations. The greater amount of incision in Richland Creek, as indicated by greater channel depths, resulted in over-steepened banks that are prone to catastrophic failure. I observed both active and dormant bank failure in every study reach located in Richland Creek. My field observations of bank failure processes in Dry Creek indicated that extensive and catastrophic bank failures occur throughout the tributary, possibly as a result of a consistent lack of cohesive bank material and/or the development of over-steepened banks from vertical incision. Widespread occurrences of bank failure in both Richland and Dry Creeks could explain the large spatial variability of channel shape observed in these two tributaries.

In contrast, field observations from Jeffers Creek showed that bank failures along this tributary were smaller in magnitude (shallow-seated) and included several reaches with inactive bank failure processes. If greater variability of channel shape in Richland and Dry Creeks is, in fact, caused by greater frequency of severe bank failures in these tributaries, then it is possible that less variability of channel shape in Jeffers Creek may be explained by a number of possibilities: 1) vertical incision in Jeffers Creek has not developed to the same extent as in Dry and Richland Creeks, 2) study reaches in Jeffers Creek have already undergone vertical and lateral adjustment phases, for some time longer than study reaches in Dry and Richland Creeks, or 3) Jeffers Creek may have better sediment connectivity that evens out channel shape differences between reaches, meaning it is able to transport its sediment load from reach to reach.

Reach-Scale Geomorphic Processes and Implications for System-Wide Response

Despite variability of channel shape within each of the study watersheds, the measurements of channel morphology and field observations suggest that channel widening and channel aggradation dominate the adjustment processes currently taking place in the tributaries. The most common stages of adjustment identified were Stage IV (Threshold) and Stage V (Aggrading). Only one reach exhibited Stage III (incising) and one reach exhibited Stage VI (re-stabilized). Other stages of geomorphic adjustment processes only identified in a few locations or not at all in this study, such as Stage I (pre-modified), Stage II (recently channelized), Stage III (incising), and Stage VI (re-stabilized), could exist within the watersheds. Reaches with these stages of adjustment were not identified because the reaches were not surveyed. While selecting study reaches, however, I made every effort to include study reaches from every sub-watershed of each study tributary. The high bank angles measured at reaches undergoing Stage IV of adjustment agree with the characterization of these reaches as being dominated by channel widening related to bank failure processes. Gently sloping bank angles found in Stage V reaches also support the characterization of these reaches as aggrading due to bank failures attaching to the base of banks, protecting the bank from future bank undercutting, and enhancing fluvial deposition.

The combined products of channel deposition and bank failure processes control the shape of cross-sections, resulting in mainly asymmetrical channel shapes. The occurrence of many reaches with characteristics of both Stage IV and Stage V adjustment processes suggests that bank protection begins on one side of the channel due to subtle reach-scale differences, such as faster bank failure rates on one bank because of a lack of stabilizing vegetation or flow constricted by bar deposits. Thus, the bank that begins failing first or most excessively reaches the protected, aggradational phase first. By virtue of developing a series of berms or deposits at its base, the protected bank initiates and/or enhances bank failure processes on the opposing bank by constricting flow towards it, until bank angles become gentle enough for bank failure processes to cease. The resulting channel shape of such reaches is highly asymmetric. Figure 3.14 shows a hypothetical sequence for the development of an asymmetric channel in the study tributaries. Figure 3.14 also shows the way channel asymmetry can be produced by bank

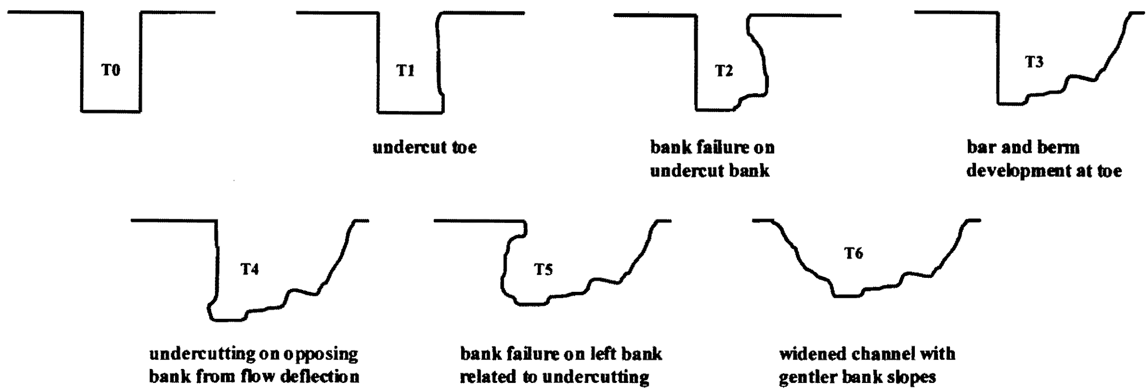

Figure 3.14: Hypothesized sequence of channel shape changes in study tributaries due to the onset of bank failure on one bank.

failure processes and sediment storage. The spatial variability and frequent asymmetric nature of channel cross-sections in study reaches is similar to a model of asymmetric channel development proposed by Knighton (1982). In the Knighton sequence, changes in sediment dynamics (sediment erosion, transport, and deposition) that are often coupled to bank erosion processes alter the channel bedform to the extent that cross-sectional asymmetry forms, and through time and over the space of the reach, asymmetric cross-sections develop and oscillate with changes in channel bedform caused by sediment dynamics. Few studies have documented varying channel asymmetry and its connection to bank processes and sediment dynamics in the field (Knighton, 1998). The results of this research provide field-based documentation of asymmetric channels and their connections to bank processes through channel sediment dynamics, such as sediment storage, in tributary streams with a history of channelization.

The results of this research also emphasize the importance of reach-scale processes during post-disturbance adjustment phases. The connections between bank failure processes, sediment storage, and the development of asymmetric cross-sectional shape occurring at the reach scale have important implications for system-wide responses and for understanding broader questions of meander development in alluvial systems. The actual processes responsible for the instigation of channel meanders in rivers are not fully understood (Hooke, 2003a). A leading explanation for meander development is the unified bar-bend theory, in which the initiation of sinuosity is preceded by the development of alternate bars, some with fixed locations and others with non-fixed locations, which determine the location of erosion and deposition downstream by deflecting flow (Knighton, 1998). Resonance or repetition of curvature downstream is hypothesized to develop after the establishment of bars with fixed locations, as flow becomes deflected in an alternating pattern, from one bank to the opposing bank downstream, and causes bank migration and increased sinuosity. Given the frequency of asymmetric (widening and aggrading) reaches throughout each of the study tributaries, channel sinuosity appears to be increasing, meaning that the interplay of bank processes and sediment dynamics at the reach scale may help determine system-wide, planform adjustments. Field-based monitoring of sediment berms and bar deposits located in widening and aggrading reaches over longer time periods could help establish whether increased channel sinuosity is occurring due to the formation of fixed bars and associated flow deflection.

Although widening and aggrading processes dominate the three study watersheds, top-of-bank w/d depth ratios suggest that the amount of widening and aggrading that has occurred varies throughout the watersheds. There is stratification of top-of-bank w/d depth ratios of the reaches surveyed, as evidenced by natural breaks in the data, which showed five groups of reaches with different ranges of top-of-bank w/d ratios. It is possible these five groups represent varying degrees of channel widening and aggrading, with reaches in groups consisting of larger top-of-bank w/d ratios, such as Jeffers Creek, having experienced a greater degree of channel widening and aggrading in the past. Jeffers Creek did not exhibit bank failures of comparable size and frequency as Dry and Richland Creeks, which may indicate that Jeffers Creek is approaching the completion of a widening/aggrading phase.

Applicability of Channel Evolution Model

I applied cross-sectional geometry measurements and bank process observations of study reaches to an existing conceptual model of geomorphic adjustment, the Channel Evolution Model (CEM) (Simon, 1994), developed for alluvial, channelized rivers. The model is largely process-based and conceptualizes adjustment as involving either aggrading or degrading processes that occur in progressive stages (I – VI), depending on the location of the reach in consideration relative to the area of maximum disturbance (AMD – the channelized reach).

I used the CEM in this study to examine its ability to help identify ongoing geomorphic adjustment processes in LHR tributary streams, which are much smaller in size than the rivers in which the model was developed. The study reaches did not entirely conform to the CEM. First, not all stages of adjustment were found. None of the 35 study reaches examined could be characterized as Stage I (pre-modified), Stage II (AMD or channelized reach), or Stage III (degrading), and only one reach was characteristic of Stage VI (restabilized). A lack of Stages I and II reaches may have resulted from very little available knowledge of the exact location of channelized reaches. A lack of Stage III reaches may indicate that vertical adjustment processes may be largely complete in the tributary streams, and may also indicate that vertical adjustment processes take less time to be transmitted through smaller, tributary streams than larger main-stem rivers. The occurrence of only one Stage VI reach might be explained by channel dredging and snagging administered sporadically by landowners in the study tributaries, which may have caused Stages IV and V adjustments to persist for longer periods of time. It is also possible that there has been insufficient time for the development of Stage VI reaches.

In any case, the emphasis given to the location of the AMD in the CEM as the focus of adjustment processes, with adjustment stages developing upstream and downstream of the AMD, is a limiting factor for its use in streams where the original location of the AMD is not known or where additional disturbances, such as channel dredging, have occurred. Additionally, approximately half of the study reaches (17 of 35) exhibited characteristics of both Stage IV (threshold/active widening) and Stage V (aggradation) adjustment. Stage IV/V reaches contained cross-sections with active bank failure occurring directly opposite banks with well-developed and attached bar/berm formations. The identification of many reaches with both widening and aggrading processes suggests that lateral migration processes are an important part of geomorphic adjustment to channelization. Lateral migration processes may be increasingly important in the adjustment of tributary streams because, as in the case of the LHR study tributaries, there may be a lack of consistent or sizeable discharges and as a result, limited or sporadic sediment transport, which may lead to substantial sediment storage. In its current version, the CEM includes lateral adjustment processes to a very limited degree by including bank failure processes in the stages of adjustment. Results of this research strongly suggest that the CEM should be amended to better include sediment storage and transport processes because sediment dynamics, in combination with bank failures, can enhance or establish lateral migration and increase channel sinuosity, as seen in the study tributaries of the LHR.

Conclusions

Patterns of geomorphic adjustment processes in alluvial, tributary streams that experienced channelization over 30 years ago show that the streams are still in a period of adjustment. The widespread occurrence of asymmetric cross-sections within each study tributary suggests that lateral migration processes are the predominant geomorphic adjustment occurring in LHR tributaries responding to channelization. Results suggest that lateral migration may be controlled by reach-scale dynamics of sediment and flow. Bank failures, storage of channel sediment in large bars and berms, and flow deflection by channel sediment deposits all act to enhance widening and aggrading processes at the reach scale and produce asymmetric channel shape. The involvement of reach-scale sediment dynamics in lateral migration processes has broader geomorphic implications in that it provides field-based observations that support bar-bend theory as an explanation for increased sinuosity and the initiation of lateral migration in alluvial rivers. However, more research is required to confirm the presence of bar-bend processes. There needs to be monitoring of channel berms/bars and flow interactions within and between reaches over long periods of time.

Current conceptual models of geomorphic adjustment in streams, such as the CEM, do not adequately incorporate lateral migration processes. Instead, vertical adjustment processes, such as channel incision and aggradation, are heavily emphasized. The CEM does consider channel widening as a response by including bank failures, but channel widening is viewed as a product of channel incision, specifically bank over-steepening and not as a consequence of accelerated channel sediment storage, as observed in tributary streams of the LHR. A significant need exists for conceptual models of adjustment, such as the CEM, to include lateral migration processes, specifically as a result of sediment storage. Sediment may be stored in channels for very long periods of time, especially in tributary streams with limited discharge for sediment transport. Therefore, channel with sediment stored in the form of bars and berms can undergo prolonged periods of channel widening and aggrading, perhaps as long as the duration of sediment storage, which may be centuries or more. Finally, the CEM may have limited application in some streams in which information concerning the location and extent of channelization is not available and in streams where additional disturbance, such as dredging, has occurred post-channelization. In both cases, the location of the AMD may not be known or may consist of multiple locations, which may mean that not all stages of adjustment may occur or be identifiable. The limitations of the CEM highlighted as result of this research have important implications for state and federal natural resource agencies and non-governmental organizations involved in watershed restoration and management, which may use the CEM for monitoring and making management decisions.

CHAPTER 4

Post-Channelization Sediment Dynamics in Alluvial Tributary Streams

This chapter is a manuscript in preparation for submission to the journal *Earth Surface Processes and Landforms.* In an effort to avoid repetition, parts of Chapter 1 that describe the physical characteristics and human history of the study site were omitted in the following discussion but will be included in the final manuscript.

Introduction

In Chapter 3, I identified spatial patterns and processes of geomorphic adjustment in three tributary streams of the Lower Hatchie River (LHR) Basin from channel morphometric measurements and observations of bank processes. Results of my analysis of geomorphic adjustment in the study tributaries suggested that reach-scale sediment dynamics are highly involved in geomorphic adjustment taking place in the study tributaries and may be involved in increased channel sinuosity and lateral migration. As discussed in Chapter 3, conceptual models of geomorphic adjustment of alluvial rivers do not adequately include lateral migration processes and the role of channel sediment in determining the spatial location and type of geomorphic processes that may occur in response to channelization in tributary streams.

More information about the frequency and duration of sediment processes in tributaries that are undergoing adjustment is needed in order to better include processes of sediment dynamics and related processes of lateral migration in conceptual models of adjustment.

Therefore in this study, I examine some aspects of sediment dynamics in the study tributaries. Questions considered as part of this study include the following:

1. How much bank material is eroded from a widening and aggrading cross-section over the course of several months? Bank failure and erosion are common sources of sediment input to the study tributaries, but little is known about the quantity of bank material eroded and the frequency with which the erosion occurs.

2. How much re-configuration and/or re-location of stored channel sediment occurs in widening and aggrading reaches over a time period spanning several months? A key factor in being able to establish the connection between channel sediment storage and lateral migration processes hinges upon determining the relative mobility of channel material and the persistence of bar and berm deposits that can be become fixed in location, cause flow deflection, and lead to widening and increased sinuosity.

3. How much time is required for a given reach in an incised and entrenched channel to re-couple with its floodplain; and, once re-coupling has occurred, what is the rate of sediment deposition? Many channelized streams are decoupled from their floodplains as a result of the channelization processes from channel deepening efforts or as a result of base level adjustment to channelized reaches.

In the study tributaries, berm and bar deposits develop as a consequence of there being a large supply of sediment from bank failures and incision but poor access to sediment storage outside of the channel because of de-coupling. Regaining access to floodplain sediment storage may be a key factor in moving beyond channel widening and aggrading phases of adjustment. However, there are no studies that suggest the length of time that is required before channels aggrade to a point that allows them to access the floodplain for sediment storage.

4. How does sediment particle size change in the study tributaries in a downstream direction? Downstream fining is often observed in fluvial systems that have relatively stable sediment dynamics (Knighton, 1998). If there is not downstream fining of channel sediment in the study tributaries, this would strongly indicate that processes of sediment dynamics are still responding to change.

Methods

Sediment Monitoring

I monitored bank erosion and change in the elevation of the channel bed at three cross-sections in Richland Creek to measure the amount of bank erosion and change in channel sediment storage that occurs over a period of months. The sediment monitoring took place in reaches R2, R4, and R6 of Richland Creek, which are shown in Figure 4.1. Figure 4.1 also shows the location of floodplain coring in Richland Creek, but the floodplain coring work is discussed in the next section.

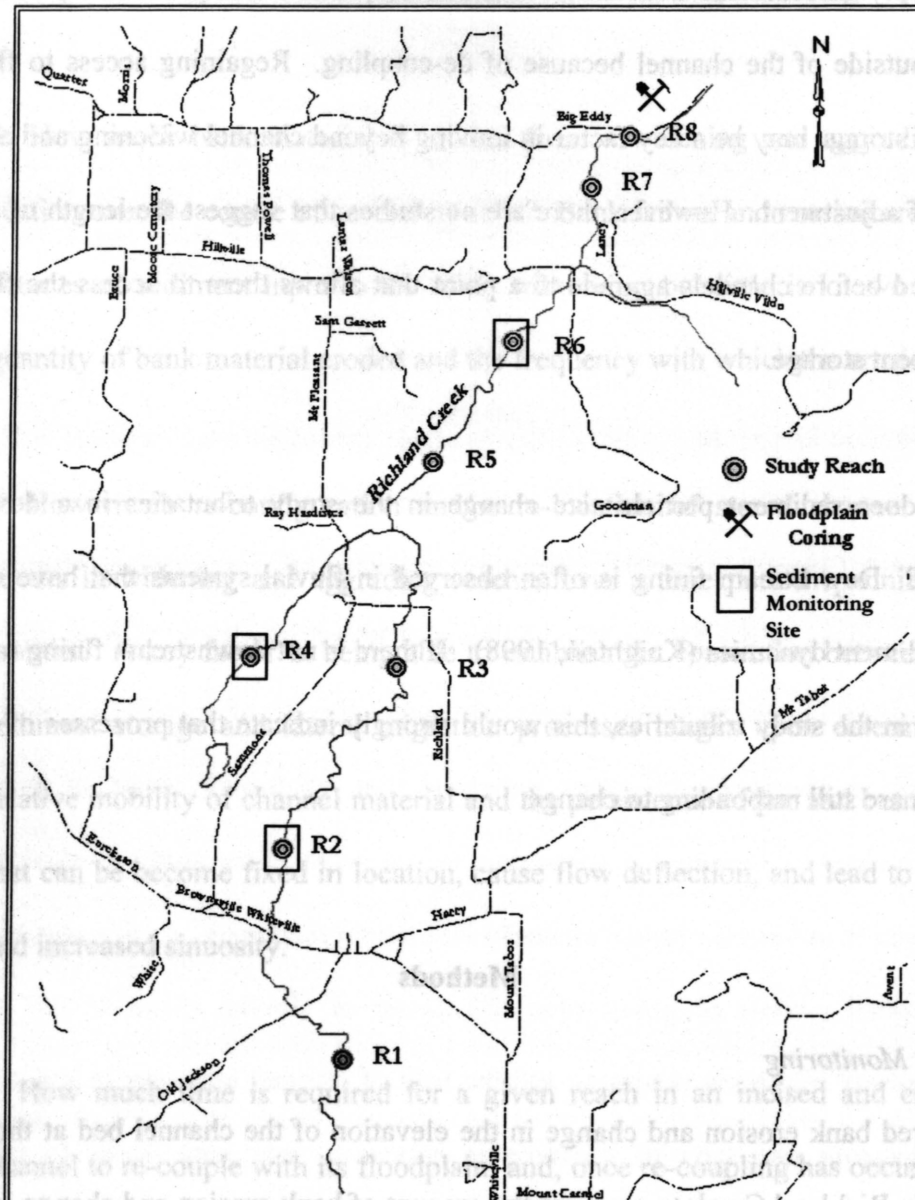

Figure 4.1: Map of Richland Creek showing the locations of sediment monitoring and floodplain coring sites.

The reaches I selected for sediment monitoring exhibited sediment processes similar to those found in many of the other study reaches, including reaches located in Dry and Jeffers Creeks. The reaches in which sediment monitoring took place all exhibited channel widening caused by bank failure on one bank, and channel aggrading processes related to channel sediment storage in berms on the other bank of the same cross-section (Figures 4.2 and 4.3). I installed monitoring equipment in June 2004 during the drier time of the year and examined the equipment for change in late December 2004 at the beginning of one of the wetter times of the year. To monitor bank erosion, I hammered 21 cm-long rebar sections into the lower bank, middle bank, and upper bank of one bank face within each study reach. I measured the length of rebar protruding from the surface (Figure 4.4). To monitor changed in the elevation of the channel bed surface that may reflect changes in channel sediment storage, I hammered in 61 cm rebar sections into the left channel, middle channel, and right channel of the cross-section's channel bed. I measured the length of rebar protruding from the surface (Figure 4.5). Very little water was present in the channel when I installed the channel rebar in June and also when I returned in December.

Floodplain Re-Coupling

To address questions of floodplain-channel re-coupling, I cored one floodplain location in Richland Creek (Figure 4.1) and dated the core sediments using ^{137}Cs concentrations. This study is the first to examine historic patterns of sedimentation from floodplain cores

Figure 4.2: Photograph of reach R2 showing sediment storage berm on left bank.

Figure 4.3: Photograph of reach R2 showing bank failure affecting right bank.

Figure 4.4: Example of bank erosion rebar deployment in Richland Creek, with rebar indicated by circles.

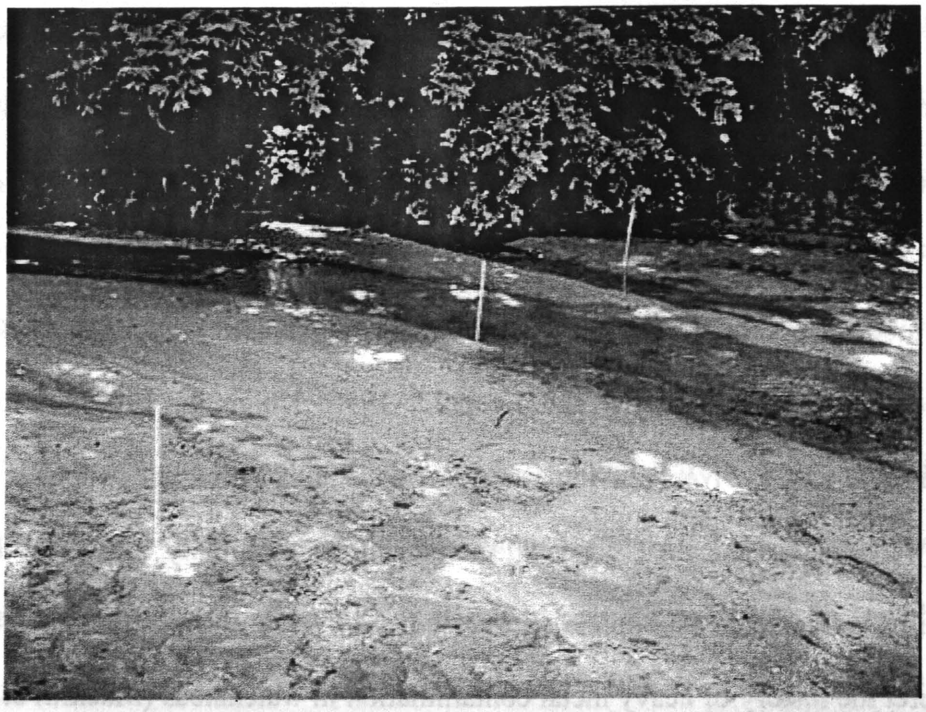

Figure 4.5: Example of channel sediment erosion/deposition monitoring rebar in Richland Creek, with painted rebar.

in west Tennessee, an area with complex watershed histories that include accelerated degradation and aggradation processes related to historic land use change, extensive agriculture, and channelization.

Human modification of river systems often results in increased production, transport, and deposition of sediment (Dunne and Leopold, 1995; Knighton, 1998). Most of the sediment produced by rivers remains within the watershed stored in floodplains (Trimble, 1977). Floodplains and their deposits, therefore, can potentially record the history of change in a watershed. Floodplain sediments from overbank deposition have been used to interpret the history of heavy metal contamination in watersheds (Macklin et al., 1994; Taylor, 1996; Hudson-Edwards et al., 1997; Macklin et al., 2003), Holocene environmental change in rivers (Taylor and Lewin, 1997), changes in sediment rates and yields through time (Rumsby and Macklin, 1994; Walling and He, 1994; Knox and Kundzewicz, 1997; Walling and He, 1999), and changes in sediment source areas through time (Passmore and Macklin, 1994; Foster et al., 1996; Collins et al., 1997; Foster et al., 1998).

The amount of time required for river systems to process sediment introduced to the system from points of origin to the mouth remains poorly understood. This uncertainty occurs because of inaccurate measurements of sediment transport because of sampling error associated with sediment sampler design, location, and the timing of sampler deployment relative to storm events. In addition, long-term records of suspended sediment transport often do not exceed 20 years of record (Owens et al., 1999). Better knowledge of the time required for fluvial systems to process human-introduced sediment can help protect aquatic habitat that may be sensitive to accelerated aggradation, permit better management decisions to be made concerning land use in watersheds, and allow the efficacy of potential stream and watershed restoration techniques to be examined.

Most of the channels in the study tributaries are de-coupled from their floodplains due to channel deepening that occurred during channelization or base level adjustment in response to channelization. Reach R8 in Richland Creek is one of the few reaches where aggradation has occurred post-channelization to the extent that the channel bed has been elevated enough to reconnect the channel with its floodplain. Three sediment cores were sampled at increasing distances from the stream channel, with the first originating at 5 m from the bank edge, the second at 10 m from the bank edge, and the third at 15 m from the bank edge, using a GeoProbe macro core sampler operated by a hired crew from Mactec Engineering. However, the core taken from a distance of 5 m from the bank edge was incomplete. The extraction of this core was abandoned in the field due to excessive wetness in the bore hole, which was causing severe loss of sample. For this reason, this core was not used in this study. The other sediment cores, located at 10 m and 15 m from the channel were extracted successfully and each was approximately 4 m in length. The GeoProbe macro core sampler hammers a metal casing, and a plastic tube positioned inside the casing, into the ground approximately 4 m deep. The metal casing with plastic tube in place is then extracted from the ground, and the plastic tube with sediment core sample inside is then extruded from the casing and capped at both ends (Figure 4.6 and Figure 4.7). The GeoProbe macro sampler is designed to provide undisturbed sediment core samples, but some disturbance of sediment layers can occur, which commonly includes compression from hammering and sloughing of material at the sides and bottoms of the core. Several of the cores with thick layers of soft, organic material appeared to have been compressed because they were shorter than 4 m, which was the sampling depth. In all cases, the soft material was located at the top of the core and each core still contained material throughout its base.

In the laboratory, I cut the cores along the long axes of the tubes, split them open, and separated the tube into two semicircular halves. One half of the tube was wrapped and preserved for archival purposes, and the other side used for stratigraphic study and sampling. The stratigraphy of each core was examined in the laboratory and visually compared to others to identify any irregularities that might be present in the depositional sequence due to spatial variation of deposition during flood events. Because I did not observe any textural irregularities among the three cores from my visual examination in the lab (Figures 4.8 – 4.10), I am only reporting results from one of the cores, the one located 10 m from the bank edge. This was 3.16 m in length and approximately 7.5 cm in diameter. There were color differences between the cores that appear to be related to varying degrees of redoximorphic processes. After opening the core, I described textural (by hand) and color changes (Munsell) visible in the core and noted the occurrence of roots and/or organic material present.

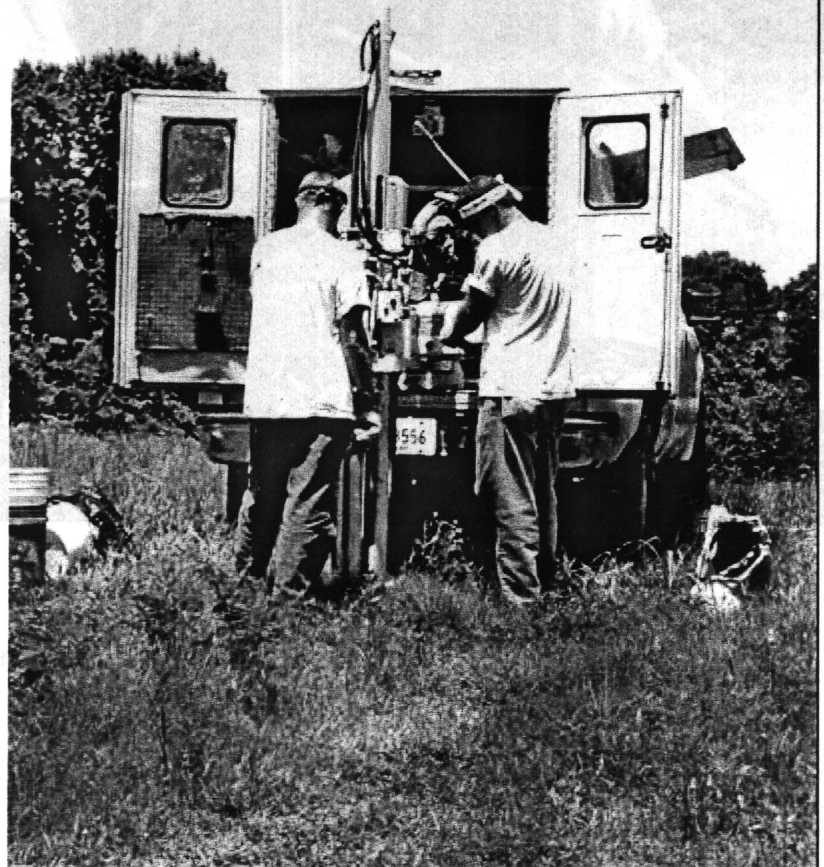

Figure 4.6: Picture showing GeoProbe rig, with Mactec personnel, hammering metal casing into ground in preparation for sediment core extraction.

Figure 4.7: Sediment core plastic tube after extraction from metal casing by Mactec personnel.

a. b.

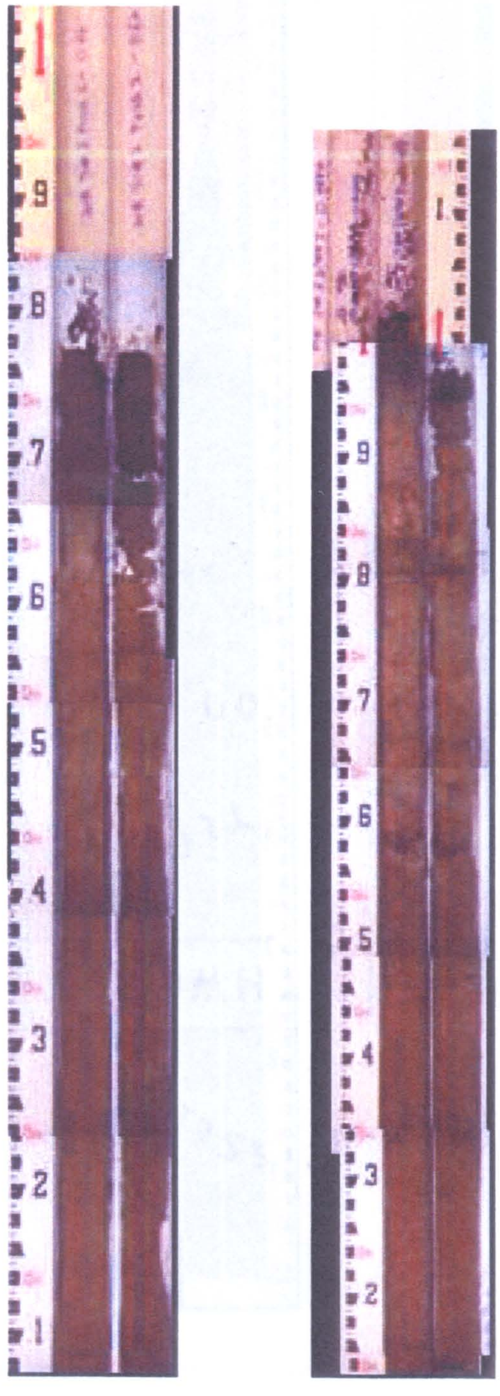

Figure 4.8: Comparison of top of core **a.** located 10 m away from channel and core **b.** located 15 m away from channel. Note that the photos were not taken at the same resolution or lighting.

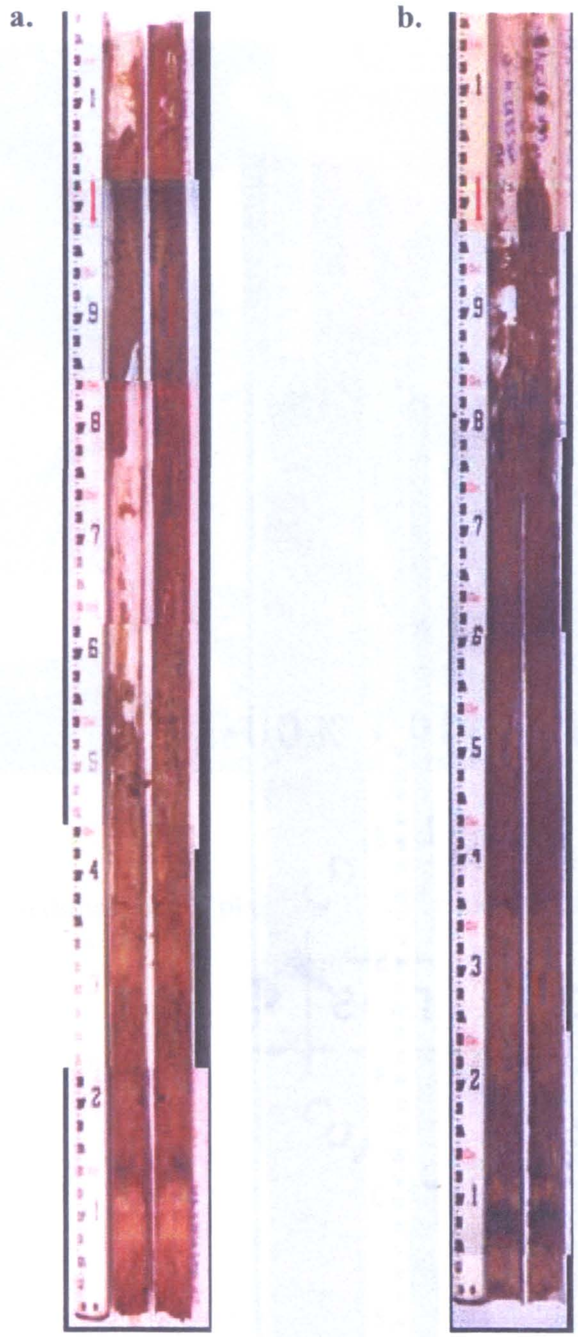

Figure 4.9: Comparison of middle of core **a.** located 10 m away from channel and core **b.** located 15 m away from channel. Note that the photos were not taken at the same resolution or lighting.

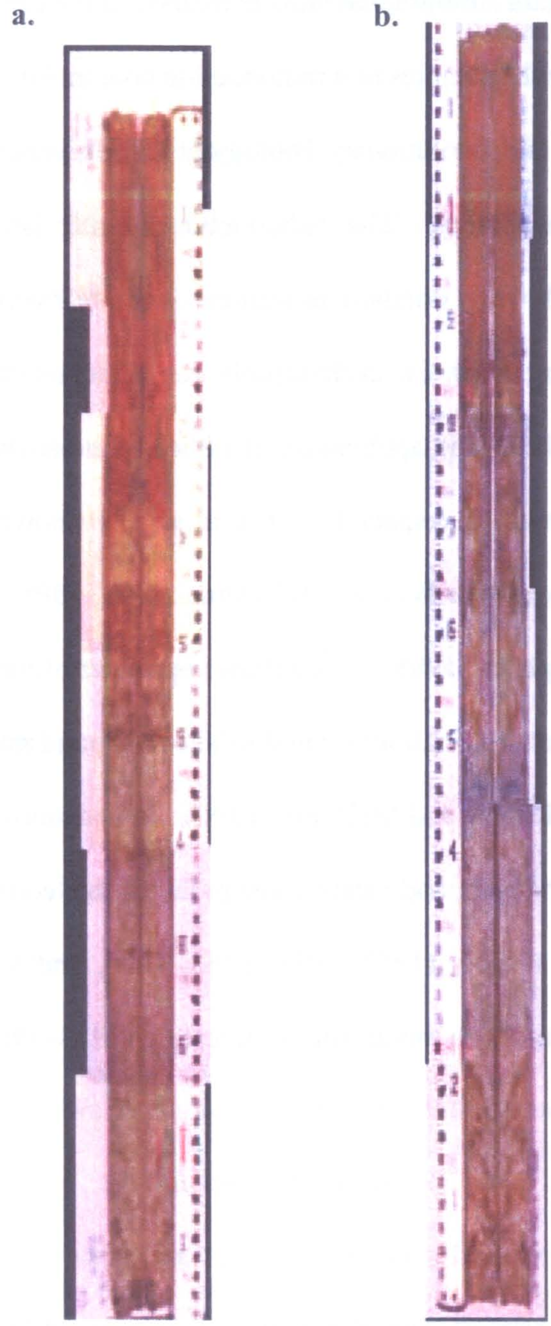

Figure 4.10: Comparison of bottom of core **a.** located 10 m away from channel and core **b.** located 15 m away from channel. Note that the photos were not taken at the same resolution or lighting. Note that the meter stick counts up in **a.** and down in **b**.

To determine the age of floodplain stratigraphic units contained in the core, I sampled the core at 10 cm intervals and sent the samples to a radionuclide counter laboratory operated by the Department of Ecology and Evolutionary Biology at the University of Tennessee for measurement of trace radioactivity. The radionuclide counter lab prepared each sample for ^{137}Cs detection following standard procedures, which involved drying and weighing each sample. During analysis, each sample remained on the radionuclide detector for a minimum of 48 hrs. The application of radionuclide analyses to develop rates of erosion and deposition, with respect to ^{137}Cs, is widely known and generally accepted (Ritchie and McHenry, 1990; Walling and Quine, 1992, 1995; Walling, 1998; International Atomic Energy Agency, 1998). ^{137}Cesium, a product of nuclear fission, is found in the natural environment from fallout related to above-ground nuclear testing or releases from nuclear reactors (Ritchie and McHenry, 1990). In undisturbed soil profiles, quantities of ^{137}Cs decrease with depth, and peaks occur in layers that correspond to years of active aboveground nuclear testing, (1952, 1958, 1963, 1971, and 1974). Lows in concentrations correspond to years with moratoriums on testing (1958–1961). ^{137}Cs has a half-life of 30.2 years.

Particle Size Analysis (PSA)

I examined changes in particle size to see if particle size decreased in a downstream direction in each study tributary, which would indicate relatively stable sediment dynamics. I sampled bed sediment throughout all three study tributaries, collecting samples from a total of 34 cross-sections. The cross-sections were located within the same study reaches in which I measured channel morphology, the results of which I discussed in Chapter 3. At each cross-section, I sampled from the active part of the channel, and dry sieved at least 200 g of each sample in the laboratory. Particle size classes used in the PSA are from the Wentworth scale include the following class ranges: ≥ 1.000 mm; < 1.000 mm – 0.500 mm; < 0.500 mm – 0.250 mm; < 0.250 mm – 0.106 mm; < 0.106 mm – 0.063 mm; < 0.063 mm – 0.053 mm; and receiving pan (< 0.053 mm). To derive the median particle size (D50) of each sediment load sample for every study reach, I calculated the cumulative frequency by weight for each Wentworth particle size class for each dry sieve sample. I used the following mathematical linear interpolation from Bunte and Abt (2001) to calculate the D25, D50, and D84 for sieved channel sediment sample.

$$Dx = 10^\wedge\{(\log(x2) - \log(x1)) \bullet [yx - y1 / y2 - y1] + \log(x1)\}$$

where:

yx = value for desired cumulative frequency

(in this case, 25, 50, or 84)

y2 = value for cumulative percent frequency below yx

y1 = value for cumulative percent frequency above yx

x2 = particle size associated with cumulative percent frequency y2

x1 = particle size associated with cumulative percent frequency y1

Results

Sediment Monitoring

The sediment monitoring conducted for seven months in selected study reaches located in Richland Creek captured a moderate amount of bank erosion but only slight change in the height of channel bed material (Table 4.1). Banks located in reaches R2 and R4 experienced some bank erosion, with a net increase in exposed bar of 2 cm and 5 cm, respectively. The main channel of reach R4 experienced a gain in sediment height of 4–11 cm, while the main channel of reach R2 experienced a loss in sediment height in its middle and right channel of 7–10 cm. The main channel of reach R6 experienced an increase in sediment height of 4–15 cm in the right and middle channel and a decrease in sediment height of 4 cm on the left channel.

Particle Size

The particle size analysis of channel sediment samples from each study tributary showed that particle sizes ranged from approximately 0.100 mm to 1.700 mm, and did not reveal a consistent linear decrease in particle size from the headwaters to the mouth for any of the study tributaries. The main channel sampling sites in Jeffers Creek exhibited more consistency in particle size than the main channel sites in Richland Creek or Dry Creek, but there were fewer main channel sites located in Jeffers Creek than in the other study tributaries. Particle sizes in Dry Creek exhibited the most spatial variability, with many increases and decreases observed throughout the tributary.

Table 4.1: Results of sediment monitoring in Richland Creek. Channel measurements with borders around them indicate that the bar was located in a berm deposit.

	Rebar Exposed			Rebar Exposed			Rebar Exposed		
Location	**R2**	**R2**	**R2**	**R4**	**R4**	**R4**	**R6**	**R6**	**R6**
	Jun. '04	**Dec. '04**	**Net Change**	**Jun. '04**	**Dec. '04**	**Net Change**	**Jun. '04**	**Dec. '04**	**Net Change**
Bank									
upper	21	21	0	21	21	0	21	21	0
middle	21	21	0	21	21	0	21	21	0
lower	21	23	-2	21	26	-5	21	21	0
Channel									
left channel	34	30	4	61	50	11	61	67	-6
middle channel	34	41	-7	61	56	5	61	46	15
right channel	34	44	-10	61	57	4	61	57	4

In Richland Creek, particle sizes ranged from approximately 0.150 mm to 0.650 mm. The overall trend for particle size change, including D25, D50, and D84, in main channel sites of Richland is steady increase in particle size from the headwaters to a peak in size that occurred in the middle reaches before a slight decrease at the mouth (Figure 4.11). This overall trend can be observed in the change of the D84. For example, the D84 at Reach R1 located at the headwaters was 0.250 mm, 0.650 mm R5 and R7 in the middle of the stream and 0.500 mm at reach R8.

The overall change of the particle size of channel material in main channel sites in Dry Creek consists of an increase in the D25, D50, and D84 from the headwaters to the middle reaches, with a decrease in particle size at the mouth that makes the particle size at the mouth similar to that of the headwaters (Figure 4.12). The D84 at reach D3, near the headwaters, and at reach D11, the mouth, were both approximately 0.600 mm, but particle size increased to a D84 of 0.800 mm at D5 in the middle of the tributary.

In Jeffers Creek, the general pattern of particle size change of main channel sites consisted of an increase in the D25, D50, and D84 from the headwater area to the middle of the tributary, a decrease in particle size near the mouth, and a slight increase in particle size at the mouth (Figure 4.13). For example, the D84 at main channel reach RB4 was

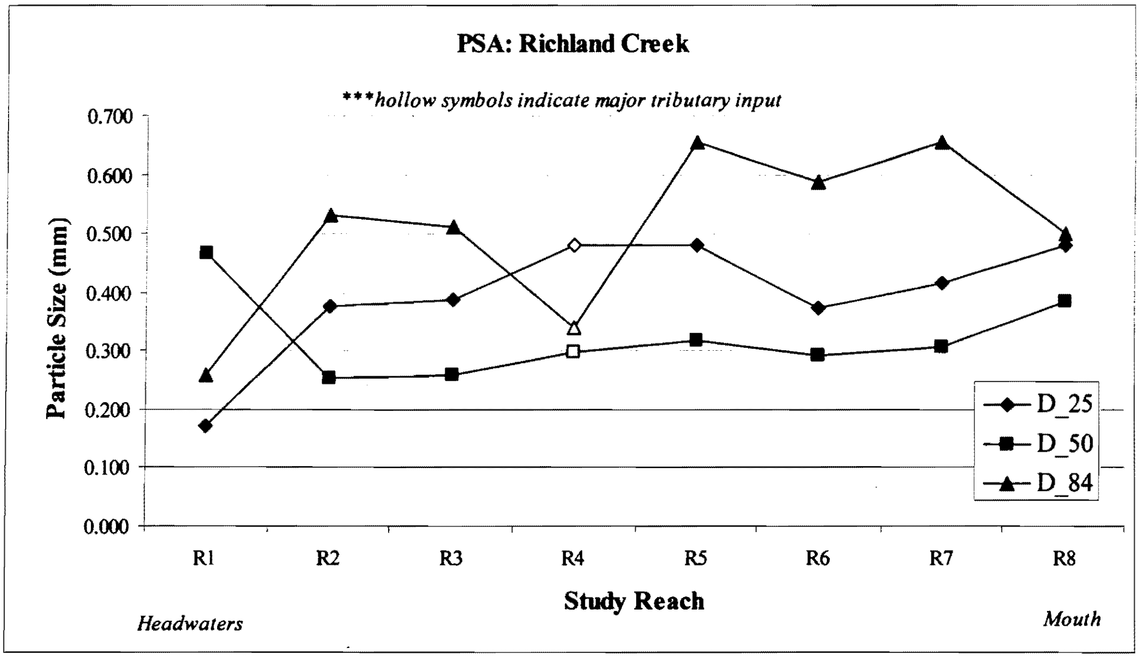

Figure 4.11: Results of particle size analysis for Richland Creek, showing the change in the D25, D50, and D84 from the headwaters to the mouth.

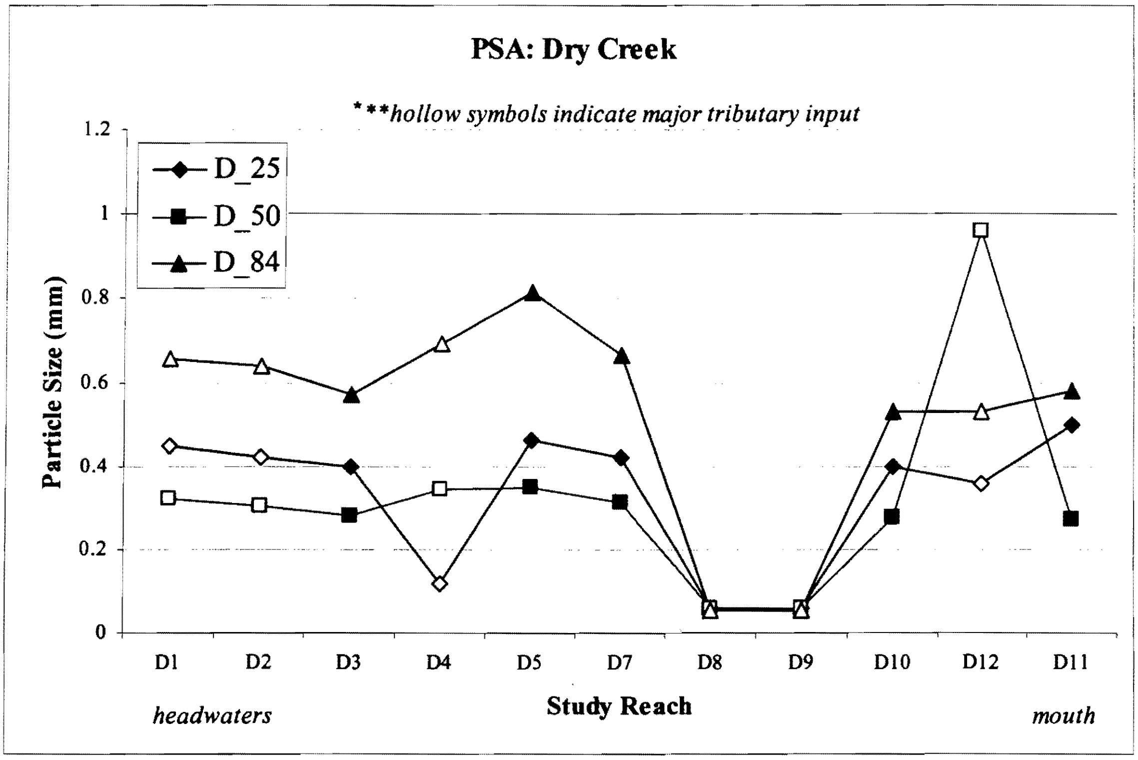

Figure 4.12: Results of particle size analysis for Dry Creek, showing the change in the D25, D50, and D84 from the headwaters to the mouth. Note that there is no sample for reach D6 and also that reaches D12 and D11, though not in numerical sequence, are presented in geographic sequence, with D11 being the mouth.

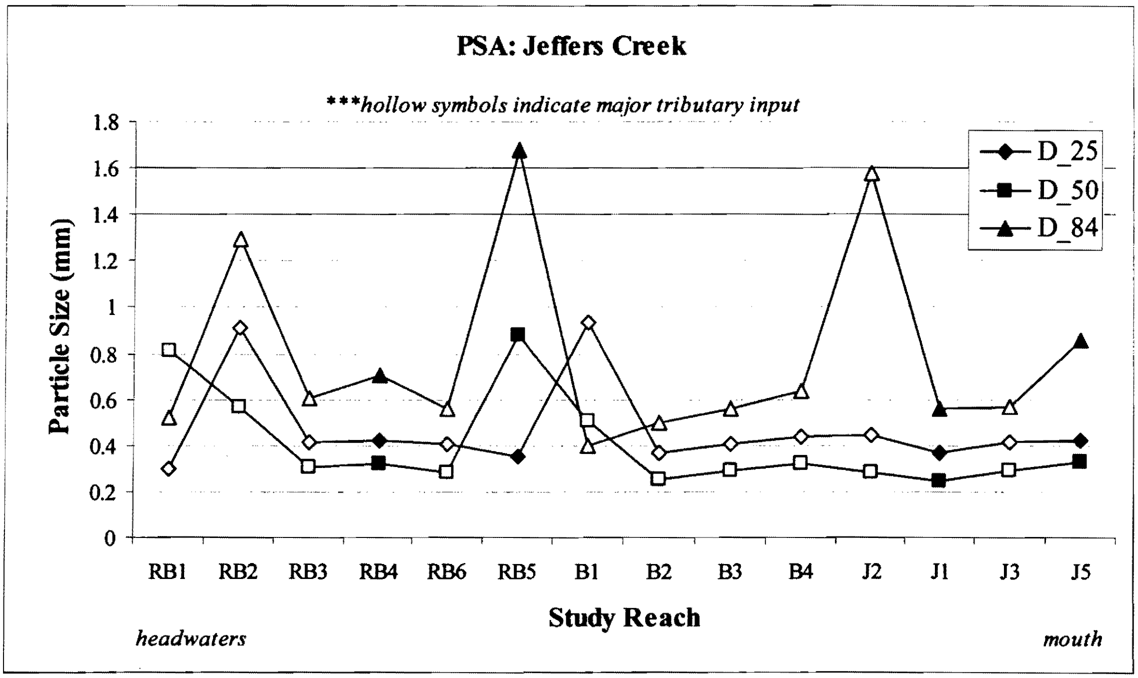

Figure 4.13: Results of particle size analysis for Jeffers Creek, showing the change in the D25, D50, and D84 from the headwaters to the mouth.

approximately 0.750 mm, 1.70 mm at main channel reach RB5, 0.600 mm at main channel reach J1, and approximately 0.900 mm at the mouth, reach J5. Jeffers Creek included several tributary drainages within it, including Rice Branch and Brown's Creek. Generally, particle sizes were larger in Rice Branch tributary sites, where the D84 ranged between 0.500 mm and 1.30 mm, than in Brown's Creek tributary sites, which had a D84 range of 0.400 mm to 0.600 mm.

Floodplain Core Stratigraphy and ^{137}Cs Concentrations

I identified 14 major stratigraphic units in the core (Figure 4.14). From 0 m to 1.40 m, I found fine to very fine sand with some clay and an accumulation of *in situ* roots. From 1.40 m to 1.55 m clay with some very fine sand was present and slight concentrations of redoximorphic features, including Fe concentrations in streaks. From 1.55 m to 1.87 m fine to medium grained sand with some clay is present and terminates with a series of thin layers, including: 1.87 m to 1.89 m – clay with very fine sand and redoximorphic concentrations of Fe; 1.89 m to 1.90 m –medium sand; 1.90 m to 1.92 m – coarse quartz sand; 1.92 m to 1.96 m – fine to very fine sand; and 1.96 m to 1.98 m – very coarse sand in a sticky, clay matrix.

After the sequence of thin sediment units, I found medium to fine sand with a few highly weathered, rounded gravels from 1.98 m to 2.31 m, followed by very coarse sand with a few rounded and weathered gravels until 2.38 m. From 2.38 m to 2.40 m, there is gleyed,

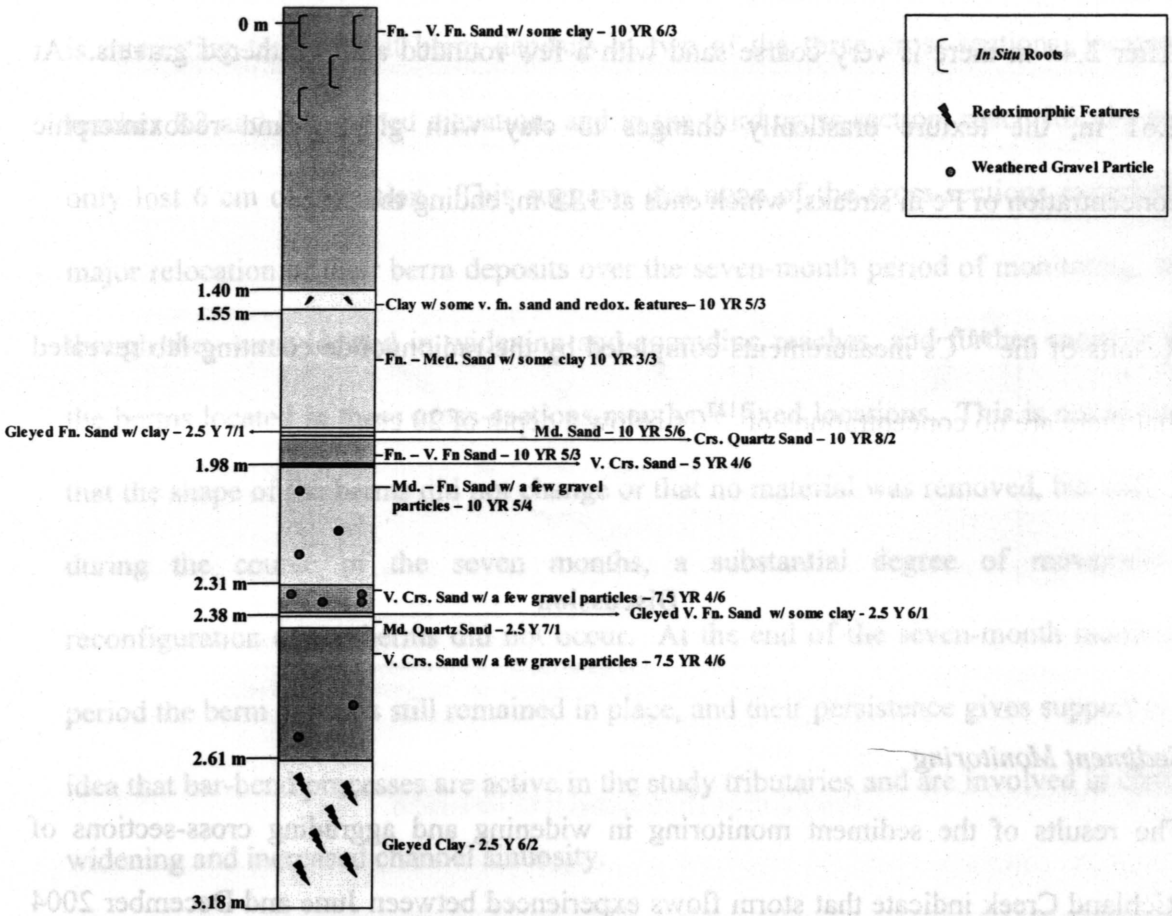

Figure 4.14: Floodplain core stratigraphy for Richland Creek, not drawn to scale.

very fine sand with some clay, and from 2.40 m to 2.44 m, there is medium quartz sand. After 2.44 m there is very coarse sand with a few rounded and weathered gravels. At 2.61 m, the texture drastically changes to clay with gleying and redoximorphic concentration of Fe in streaks, which ends at 3.18 m, ending the core.

Results of the ^{137}Cs measurements completed by the radionuclide counting lab revealed that there are no concentrations of ^{137}Cs below a depth of 20 cm.

Discussion

Sediment Monitoring

The results of the sediment monitoring in widening and aggrading cross-sections of Richland Creek indicate that storm flows experienced between June and December 2004 contributed to bank erosion but were not sufficient, either in size or number, to transport or re-configure large amounts of material stored in the channel. Two of the three bank faces monitored experienced several centimeters of erosion on their lower banks. Although the lower bank erosion did not induce a catastrophic bank failure, the erosion of several centimeters of material at two of the sites gives some support to the idea that bank failures in the study tributaries are a progressive process related to bank undercutting, as postulated in Chapter 3, and not just toppling of banks that are over-steepened by channel incision. There was some change in the height of the sediment stored in the channel bed, with two of the three cross-sections exhibiting a net gain in channel sediment elevation and the other, reach R2, exhibiting a net loss in channel sediment elevation. However, it is interesting to note that berm deposits in two of the three cross-sections, located in reaches R2 and R4, gained elevation, and in the third cross-section, reach R6, the berm only lost 6 cm of elevation. This suggests that none of the cross-sections experienced major relocation of their berm deposits over the seven-month period of monitoring, even though they were located in widening and aggrading reaches, and further suggests that the berms located in these cross-sections may have fixed locations. This is not to imply that the shape of the berms did not change or that no material was removed, but only that during the course of the seven months, a substantial degree of movement or reconfiguration of the berms did not occur. At the end of the seven-month monitoring period the berm deposits still remained in place, and their persistence gives support to the idea that bar-bend processes are active in the study tributaries and are involved in channel widening and increased channel sinuosity.

It is possible the berm deposits were not substantially disturbed because there was a lack of sufficient storm flows during the seven-month monitoring period. The study tributaries are ungauged basins. There are no discharge records. But the potential for the precipitation that occurred during the monitoring period to generate storm flow is indicated by the daily mean discharge data for the Lower Hatchie River at the USGS gauging station located approximately 48 km away from Richland Creek, in Bolivar, Tennessee. The gauge record (Figure 4.15) shows that the daily mean discharge for the

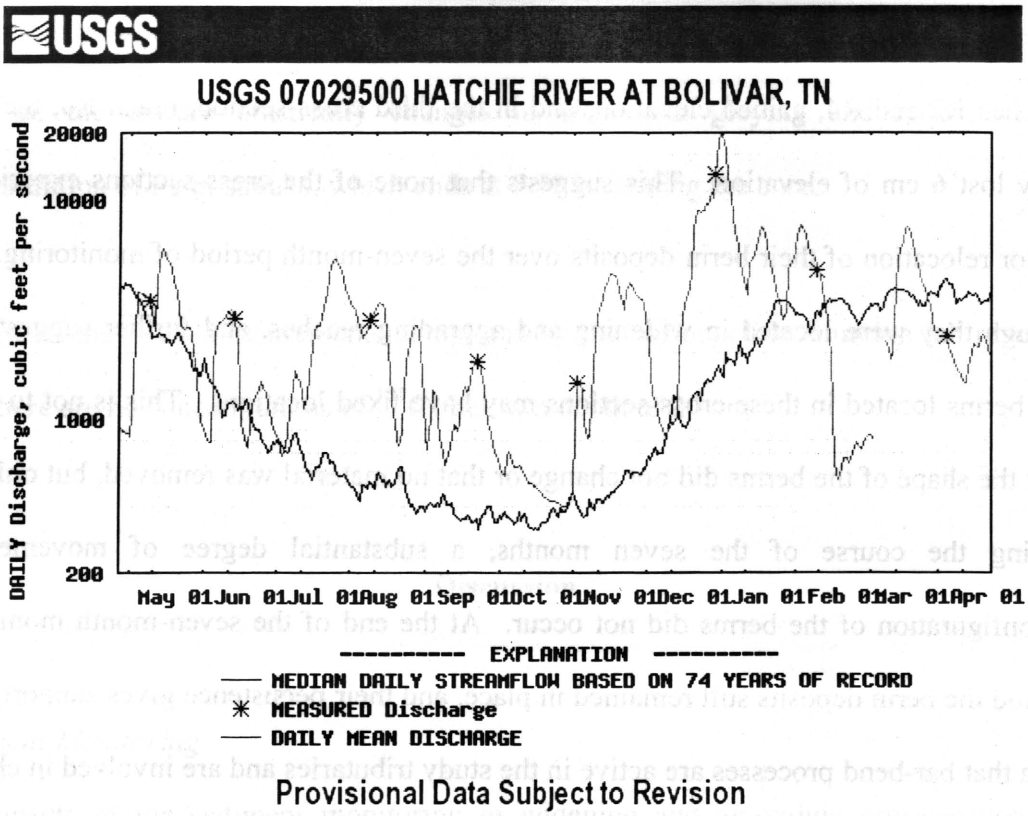

Figure 4.15: Daily mean discharge from May 2004 – April 2005 and the median monthly discharge for a 74-year period of record from the Lower Hatchie River at Bolivar, TN (U.S. Geological Survey, 2005).

months of June through December, 2004 were all above the median monthly discharge calculated from a 74-year period of record. Therefore, the precipitation events that occurred during the monitoring period were significant enough to generate above average discharges in the Lower Hatchie River.

Particle Size Analysis

Results of the particle size analysis of channel material did not reveal a consistent, downstream linear decrease of D25, D50, or D84 particle sizes in any of three tributaries. Of the three study tributaries, Jeffers Creek exhibited the most consistency of particle size in its main channel study reaches. The lack of a consistent decrease in particle size along the profile of the study streams may be related to several factors. Bank failures occur throughout each of the study tributaries. Therefore, increases and decreases of particle size must be related, to a certain degree, to localized sediment sources. In addition, results of the sediment monitoring suggest that some sediment is being stored in channels for long periods of time. It appears that sediment movement is irregular. Additionally, the results of the particle size analysis did not appear to show any instances where changes in particle size exhibited in the main channel could be related to tributary inputs, which implies that there is a disconnect between reaches in regards to their sediment transfer. The study tributaries are relatively low-gradient, alluvial streams, but in terms of sediment transport, they may function similarly to mountain streams because of the limited discharge available to them on a daily basis. Sediment dynamics in tributary streams may require longer time periods to adjust to channelization and other disturbance because of their limited ability to process sediment, unlike larger, main stem rivers that have more consistent discharge available to transport sediment. Reaches that are de-coupled from their floodplains may have their sediment transport ability even further limited because the sediment cannot exit the channel.

Floodplain Re-Coupling

I noted a considerable amount of textural and color change in the sediment core material, which may represent a long record of watershed history spanning centuries or more. At the time of analysis, however, only limited ^{137}Cs dating was available, which can date material deposited in recent decades. Therefore, the full stratigraphic record of Richland Creek represented in the sediment core could not be interpreted.

The ^{137}Cs analysis did not detect ^{137}Cs below a depth of 20.0 cm. The absence of ^{137}Cs concentrations in material at depths > 20 cm suggests that this material was deposited prior to the year 1952– the first year of ^{137}Cs fallout. This means that in the past 53 years a minimum of 20 cm of sediment has been stored in the floodplain of Richland Creek. From the ^{137}Cs information, a crude, average sedimentation rate can be calculated, which equals 0.38 cm/yr. An average rate of deposition of 0.38 cm/yr seems a relatively low rate of sedimentation for a floodplain located at the mouth of an alluvial river located in the southeastern U.S. The relatively limited sediment deposition may indicate a lack of sufficient storm events to carry sediment out of the channel, but is more likely to be related to the re-coupling between the channel and floodplain being relatively recent, within the last decade perhaps. The results of the ^{137}Cs analysis suggest it has taken over 50 years for the floodplain and channel to re-couple. If this is the case, it means that a relatively long period of time is required, in terms of a human timescale, for floodplain storage to be re-instated into the fluvial system post-channelization. In terms of sediment dynamics and geomorphic adjustment processes, prolonged de-coupling of channels from their floodplains could mean continued channel widening related to storage of sediment in the channel in the forms of berms and bars.

Conclusions

Existing conceptual models of geomorphic adjustment focus on vertical processes of adjustment, such incision and aggradation. However, results of my study of spatial patterns and processes of geomorphic adjustment in three tributary streams of the LHR, which were discussed in Chapter 3, suggested: 1) lateral adjustment processes may dominate tributary streams after an initial period of downcutting, 2) sediment dynamics, especially processes related to sediment storage, are heavily involved in determining the spatial location of geomorphic processes, and 3) widening processes may be prolonged due to long-term storage of sediment within the channel.

Results from the study of sediment dynamics in alluvial, tributary streams of the LHR presented in this chapter indicate that sediment dynamics in the streams are still in a state of adjustment and that a large part of the adjustment taking place revolves around a lack of sediment storage options. These results have important implications regarding the types of geomorphic adjustment processes that can occur in response to channelization and the use of numerical models of sediment and adjustment processes in tributary streams.

Results of the sediment monitoring suggested that bank erosion processes are progressive and that sediment berms and bars formed in the channel do not relocate on a regular or short-term (days) basis but, instead, persist for at least several months. The persistence of berm/bar deposits in cross-sections experiencing both widening and aggrading processes lends support to the idea that bar-bend processes may be operating in the study tributaries and that lateral migration processes have an important role in the response of tributary streams to channelization.

Re-coupling of channelized reaches and their floodplains appears to require more than 50 years and has occurred relatively recently in only one reach of Richland Creek, the focus of the floodplain coring work. The lack of floodplain/channel coupling means that sediment will continue to be stored within the channel in berms and bars, which may cause widening and aggrading processes to persist well into the future.

The particle size analysis suggested that there is no decrease in particle size in a downstream direction in any of the study tributaries, although there was some consistency of particle size in main channel sample locations of Jeffers Creek. A lack of hydraulic sorting of sediment in the streams suggests poor sediment transfer between reaches and the dominance of reach-scale sediment sources. The dominance of reach-scale sediment sources is an important observation because, in terms of sediment processes, there is often an emphasis placed on watershed sources (Lane, 1995), especially in numerical modeling of watershed processes. The particle size analysis suggests that watershed-scale processes of sediment dynamics are not as significant in tributary streams adjusting to channelization as reach-scale sediment sources. The use of numerical models of sediment processes in ungauged basins has become commonplace. Numerical models of sediment transport, however, may provide erroneous results in ungauged basins similar to the study tributaries, in which localized sediment sources dominate.

CHAPTER 5

Sediment Connectivity in Tributary Streams

This chapter is a manuscript in preparation for submission to the journal *Earth Surface Processes and Landforms*. In an effort to avoid repetition in the dissertation, parts of Chapter 1 that describe the physical characteristics and human history of the study site are omitted in the following discussion but prior to submission will be included in the final manuscript.

Introduction

Rationale

Many difficulties are associated with directly measuring bed material transport and behavior, mainly concerning the design of monitoring devices and temporal variation in rates of bed sediment transport (Knighton, 1998). An acute need exits to develop a method of simulating bed material movement and storage through river networks over time, because temporarily stored channel sediment can be a long-term source of water contamination and aquatic habitat impairment (James, 1999). Some researchers (Brasington *et al.* 2003) have quantified sediment transport using data on channel morphology derived from remote sensing techniques, such as LIDAR. Not all watersheds have this type of remote sensing data available, however, and the acquisition of such data can be prohibitively expensive, especially if a time series is required that would necessitate repeated collection of remotely sensed data. Because of the difficulty of field-based measurement and the potential expense associated with remote sensing-based research of sediment dynamics, many researchers utilize numerical models of fluvial processes to understand sediment dynamics.

Most numerical modeling studies that address issues of sediment dynamics in fluvial systems revolve around system-wide response to change, such as tectonic change (Willgoose *et al.*, 1991; Howard, 1994), and climate and land cover change (Coulthard and Macklin, 2001; Coulthard *et al.*, 2002) and its effects on sediment dynamics. However, sediment dynamics in fluvial systems are determined by both external controls, such as land use, and internal controls, such as bank failure (Paola, 2003), which makes accurately simulating sediment dynamics in watersheds difficult regardless of the approach (Coulthard *et al.*, 2005). There have been many attempts to accurately model sediment dynamics in fluvial systems, but none are universally applicable because they are not dynamic enough to accommodate the changing (over time and space) importance of internal and external factors of sediment dynamics from system to system (Coulthard *et al.*, 2005). Non-linear sediment dynamics are often caused by reach-scale sediment processes, such as mass movements and bar translocation, and reduce the efficacy of numerical models to accurately predict variables of sediment dynamics (Coulthard, 1998).

Results of research presented in Chapters 3 of this dissertation suggested that reach-scale sediment dynamics are heavily involved in determining geomorphic adjustment processes and their spatial locations in the study tributaries. The results of the particle size analysis and sediment monitoring presented in Chapter 4 suggested that sediment transfer in the study tributaries is irregular. But without monitoring reach-scale sediment dynamics over a long period of time and at many locations, it is difficult to say if this is indeed the case. Therefore, in this study I examine the possibility of using channel morphology measurements to examine sediment connectivity or transfer in three channelized, tributary streams of the LHR. Evidence of channel morphologic similarity or dissimilarity in the study tributaries would help determine if sediment transport is irregular in the study tributaries.

Fluvial System Coupling, Connectivity, and Continuity

System coupling, connectivity, and continuity are based on the generally held assumption that the various components of a river function as an interconnected system (Schumm, 1977). Coupling can be observed at several different spatial scales, including the reach scale (banks to channel), basin scale (uplands to lowlands), and even region scale (climate and discharge) (Harvey, 2000).

Connectivity refers to whether or not different components of a river system are physically linked by geomorphic processes, such as sediment delivery, sediment entrainment, or sediment deposition. Connectivity may also include identifying the discharge conditions under which the connections may become active – storm flows versus baseflow, for example.

Sediment connectivity, as described by Hooke (2003b), is particle transfer from one section of the channel into another section. It may involve sand bar to sand bar, reach to reach transfer, or other modes of sediment transfer. Hooke (2003b) distinguished sediment connectivity from sediment continuity, which describes the transfer of a certain particle *class* but does not describe the transfer of *a* particular particle from one place to another. As such, the relative connectivity of sediment between stream segments reflects dynamic processes of sediment entrainment, transport, and storage. Understanding spatial and temporal variations in system connectivity is significant to understanding geomorphic adjustment because changes can be absorbed, translated, and/or mitigated depending on the degree of connectivity between the different components of the system (Fryirs and Brierley, 1999; 2001). In addition, connections within a system evolve over time and space, varying with external variables (such as climate) and internal dynamics of the system (such as sediment exhaustion) (Harvey, 2002).

Channel morphology or cross-sectional form is determined by the discharge, bed-load transport dynamics, and the composition and relative erodibility of channel bed and bank boundary layers (Knighton, 1998). The characteristics of these three controls vary throughout a system primarily as drainage basin geology changes and drainage basin area increases or decreases (determines discharge). Sediment dynamics (i.e., sediment transport, deposition, and storage) co-vary with channel shape in response to variable geology and drainage basin area. Therefore, changes in channel shape are, to a certain extent, a product of temporal and spatial variability of sedimentation processes.

Methods

Channel Morphology

I surveyed channel morphology in 34 reaches in the three study tributaries of the Hatchie River in west Tennessee: Richland Creek, Dry Creek, and Jeffers Creek. I considered reaches to be smaller lengths of stream (around 100 m in length) having similar channel shape and geomorphic processes, and stream segments to be larger lengths of stream (1 km or greater in length) produced by spatial variability of sub-watershed drainage area. Please refer to Chapter 3 for detailed discussion of the study reach selection process and collection of the channel morphology measurements. I surveyed a distance of 50 m to 100 m within each study reach and ensured these reaches were located upstream and downstream of stream junctions because of changes in sediment load that occur with input from tributary streams (Ichim and Radoane, 1990; Rice and Church, 1996). In this analysis, I use the field-measured parameters of bankfull width and bankfull depth, from which I calculated bankfull cross-sectional area and bankfull width/depth ratio.

Bankfull stage is the height of a discharge at which the channel capacity reaches its maximum. Beyond this stage, the river overflows its banks and floods (Goudie *et al.*, 1994). Bankfull stage occurs on average every 1.5 years, suggesting that it represents a discharge of moderate magnitude that occurs with relative frequency (Leopold *et al.*, 1964). Given its frequency and magnitude, bankfull discharge is often equated to the effective or dominant discharge, which is the discharge that determines the average size and shape of a channel (Goudie *et al.*, 1994). Many studies support treating bankfull discharge as the effective discharge (Andrews, 1980; Ackers, 1992; Andrews and Nankervis, 1995; Batalla and Sala, 1995), while other studies do not (Baker, 1977; Pickup and Warner, 1976; Ashmore and Day, 1988; Nash, 1994). This issue remains unresolved because not enough field validation has been conducted to definitely say when the most geomorphic work is accomplished, i.e., during bankfull discharge, during high magnitude/low frequency flows, or during high frequency/low magnitude flows. Any one discharge of a particular frequency or magnitude is unlikely to shape the channel and control sediment dynamics. Instead, it is more likely that a range of flows is involved (Pickup and Warner, 1976; Andrews, 1980; Nash 1994).

I chose to work with bankfull morphometrics because the study streams are deeply entrenched with bank heights that range from 2 m–4 m, either as a direct consequence of the channelization (ditching to restrict flooding) or indirectly through base level adjustment in non-channelized reaches in response to base level lowering due to ditching in channelized segments downstream. Under the current climatic regime, it is unlikely that any discharge that occurs in these streams will ever reach or exceed 4 m (the maximum bank height observed in the field), so I measured the width and depth at the stage that best reflected the effective discharge (Bunte and Abte, 2001). Additionally, the three study streams are ungauged basins, meaning there are no discharge records from which to calculate flow duration curves or to generate sediment transport rates.

Therefore, field determination of bankfull stage offers a discharge to work with in a study location that otherwise would have none.

Sediment Connectivity

I examined continuity (similarity) of reach morphology throughout each study watershed using a non-parametric statistical technique called "multi-response permutation procedure" or MRPP. Its application, like other permutation tests, has only recently become more widespread in the scientific community with the advent of faster and better processing capabilities in personal computers (Good, 2000), but the test is not commonly found in commercially available statistical software. I used a statistical program called "Blossom," developed by the United States Geological Survey to conduct MRPP analysis (U.S. Geological Survey, 2001).

I tested for similarity of the channel morphologic variables measured in the field, which would indicate continuity of channel morphology and, by logical extension, sediment connectivity. I used the channel dimensions measured at the primary cross-sections of study reaches to compare the channel morphology of reach pairs. Reach pairs consisted of an upstream and downstream reach from each stream segment within each study watershed. MRPP can be used to test for similarity or dissimilarity between pre-defined groups, in this case reaches (Orlowski *et al.*, 1995). MRPP first calculates the average intragroup distance between grouped observations in Euclidian geometric data space, weighted by the number of observations. This provides a test statistic based on the average distance between intragroup observations within the group in Euclidian space called the observed delta or δ_{obs}. The observed delta is compared to the predicted deltas (δ) generated from the average distances for all other possible groupings or permutations of the data within Euclidian data space. Based on a comparison of the observed and predicted deltas, the probability of achieving the same grouping of the observed data by random chance is calculated, providing a p-value (Orlowski *et al.*, 1995). Therefore, the statistical analysis results in two measures: 1) the observed delta that can be used to infer the degree of clustering of observations in data space within groups, and 2) a probability value, which can be interpreted as the likelihood that the pre-defined groups being compared belong to the same sample population.

For each watershed studied, I grouped the measurements of channel morphology by reach and tested adjacent reaches for similarity in shape. If the p-value for a reach pair comparison was < 0.05, then I considered the channel morphologies of the reach pair to differ significantly. Additionally, I considered the channel morphologies of reach pairs with p-values > 0.05 to have no significant difference and, therefore, to have similar channel shape. I interpreted reach pairs indicated by MRPP to be morphometrically dissimilar as exhibiting discontinuity in channel morphology between them. I interpreted a lack of significant change in channel morphology between reach pairs as similarity in channel morphology and, therefore, channel morphologic continuity between the reaches. The spatial pattern of channel morphologic continuity and discontinuity was mapped for each watershed.

Results

Channel Morphology Continuity

I discussed the channel morphology measurements in Chapter 3, and summarized them in Tables 3.5–3.7. The MRPP statistical analysis indicates the degree of continuity in channel shape varies considerably between the three study watersheds. No study watershed exhibited reach continuity throughout its entire length, but Jeffers Creek exhibited the most channel morphologic continuity and Dry Creek the least.

Table 5.1 summarizes the p-values associated with each reach pair and the test statistics for the morphologic variables analyzed during the MRPP for Richland Creek. Three pairs of reaches, R2/R3, R6/R7, and R7/R8, each located within different stream segments of the watershed, were morphologically similar, having p-values > 0.05. Of the variables analyzed, bankfull depth had the highest degree of clustering, indicated by observed deltas of < 1 in all cases. Bankfull width, bankfull width-to-depth ratio, and bankfull cross-sectional area, however, had observed deltas > 1, indicating poor clustering of these variables. The similarity of channel shapes between R2/R3, R6/R7, and R7/R8 defines two separate segments of Richland Creek with continuity in channel shape. The spatial pattern of morphologic continuity in channel shape for Richland Creek (Figure 5.1) reveals one stream segment in the upper portion and one stream segment in the lower portion with localized continuity of channel morphology.

Table 5.1: Results of MRPP analysis for Richland Creek, showing observed deltas for channel morphology variables and p-values for reach pairs. Bold faced p-values suggest similarity at the 0.05 level or higher.

Reach Pair	Depth	Width	W/D Ratio	X-Sect. Area	P-Value
R1/R2	0.597	3.926	4.525	6.303	0.025
R2/R3	0.313	4.361	3.941	6.011	**0.285**
R3/R4	0.527	3.392	3.889	6.058	0.027
R4/R5	0.535	5.133	3.011	10.194	0.025
R5/R6	0.820	4.806	25.043	12.837	0.023
R6/R7	0.144	2.160	17.674	1.771	**0.080**
R7/R8	0.088	1.158	8.197	1.019	**0.097**

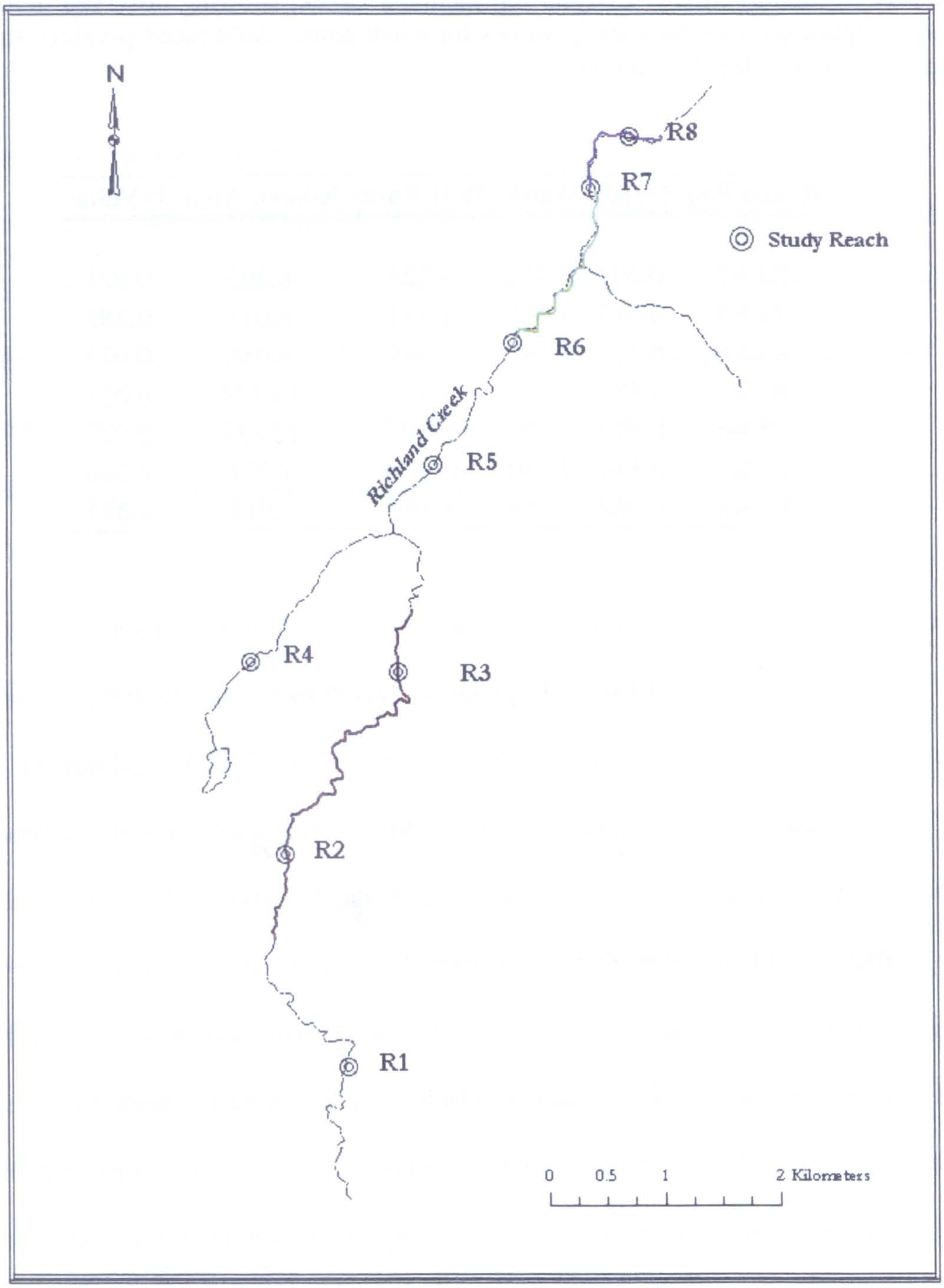

Figure 5.1: Spatial pattern of channel morphologic continuity in Richland Creek derived from MRPP analysis. Reaches mapped in the same color have similar channel shapes.

Table 5.2 summarizes the p-values associated with each reach pair and the test statistics for every morphologic variable analyzed during the MRPP analysis for Dry Creek. P-values > 0.05 occur with reach pairs D1/D3, D3/D5, and D4/D5, suggesting similarity in channel morphology within each reach pair.

The channel morphology variable with the greatest degree of clustering in Dry Creek is bankfull depth, because the observed deltas for this variable are all < 1. Poor clustering occurs with bankfull width and bankfull width-to-depth ratio. Good clustering of bankfull cross-sectional area occurred with reach pairs D1/D2, D6/D7, D7/D8, D7/D9, and D7/D10, all of which had observed deltas of < 1.

The similarity of channel morphology between reach pairs D1/D3, D3/D5, and D4/D5 results in one long segment of Dry Creek with continuous channel morphology (Figure 5.2). The sequential stream segments with channel morphologic continuity in Dry Creek watershed begin in a headwater tributary at reach D1, and terminate in the middle reaches of the main channel at D7.

Results of the MRPP analysis for Jeffers Creek are summarized in Table 5.3, showing the p-values associated with each reach pair and the test statistics for every variable analyzed. P-values > 0.05 occur for several reaches in Jeffers Creek, including: B1/B3, B3/B4, RB4/RB1, RB4/RB2, RB4/RB3, RB4/RB6, and J1/J5, and suggest similarity of reach channel morphology between the reach pairs.

Table 5.2: Results of MRPP analysis for Dry Creek, showing observed deltas for channel morphology variables and p-values for reach pairs. Bold faced p-values suggest similarity at the 0.05 level or higher.

Reach Pairs	Depth	Width	W/D Ratio	X-Sect. Area	P-Value
D1/D2	0.142	1.04	59.969	0.617	0.023
D1/D3	0.13	1.795	8.983	1.272	**0.846**
D3/D4	0.128	1.401	5.903	1.23	**0.911**
D3/D5	0.13	5.448	28.569	1.468	**0.088**
D4/D5	0.045	5.34	28.692	1.04	0.032
D5/D6	0.076	5.682	31.446	1.09	0.033
D5/D7	0.029	4.75	20.728	1.119	0.044
D6/D7	0.095	1.942	16.135	0.687	0.041
D7/D8	0.021	3.959	22.628	0.712	0.023
D7/D9	0.041	4.02	21.329	0.801	0.023
D7/D10	0.057	3.326	17.607	0.891	0.025
D10/D11	0.224	2.822	24.587	2.948	0.024
D10/D12	0.092	5.754	27.049	1.368	0.025
D11/D12	0.271	7.379	13.998	4.225	0.023

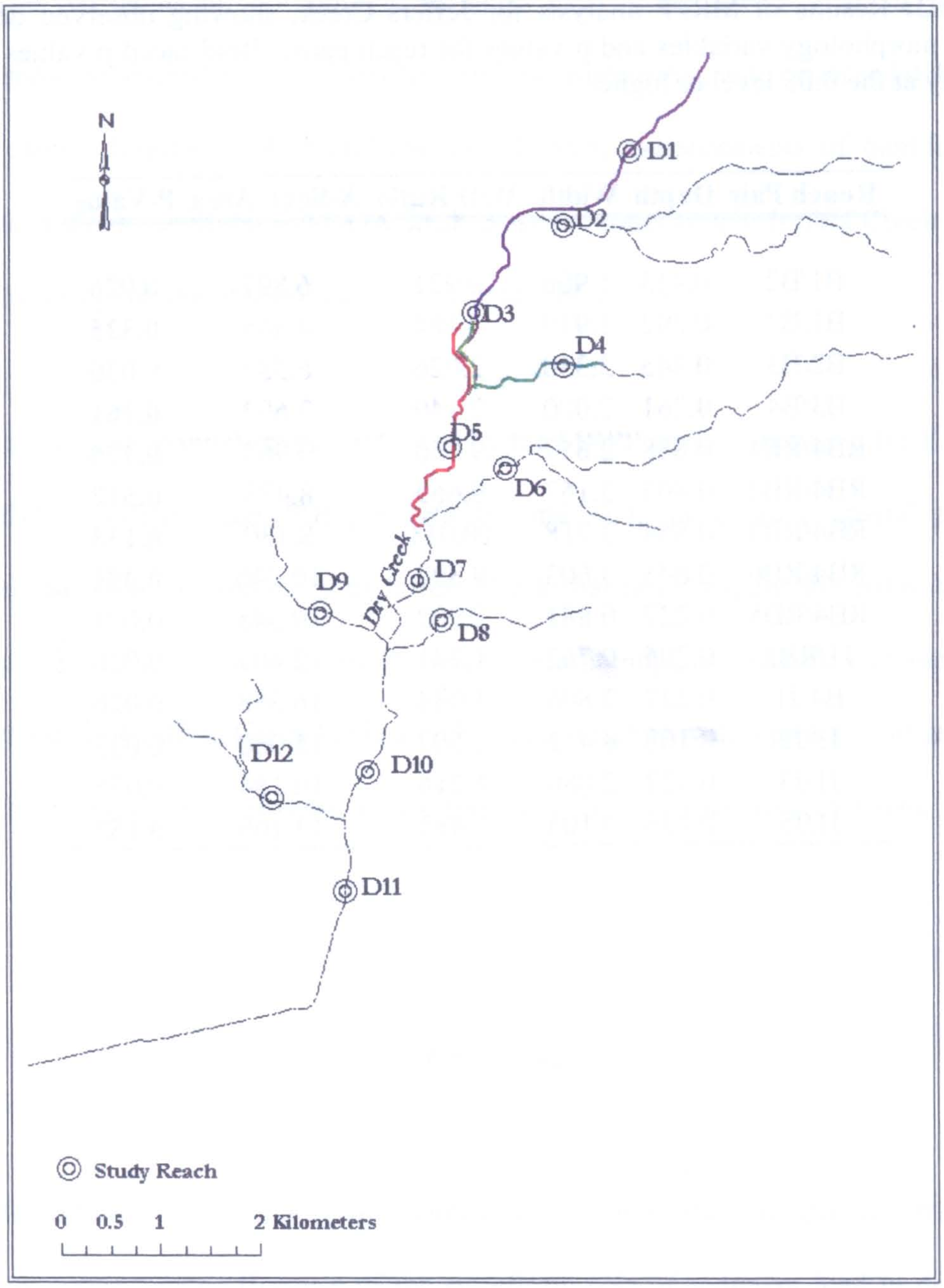

Figure 5.2: Spatial pattern of channel morphologic continuity in Dry Creek derived from MRPP analysis. Reaches mapped in the same color have similar channel shapes.

Table 5.3: Results of MRPP analysis for Jeffers Creek, showing observed deltas for channel morphology variables and p-values for reach pairs. Bold faced p-values suggest similarity at the 0.05 level or higher.

Reach Pair	Depth	Width	W/D Ratio	X-Sect. Area	P-Value
B1/B2	0.415	1.906	0.921	6.897	0.026
B1/B3	0.292	1.919	2.184	4.866	**0.325**
B2/B3	0.345	3.330	2.026	6.587	0.030
B3/B4	0.261	2.000	2.140	3.602	**0.261**
RB4/RB1	0.838	2.657	9.750	9.963	**0.776**
RB4/RB2	0.803	3.157	9.663	8.475	**0.512**
RB4/RB3	0.854	3.718	10.011	8.130	**0.133**
RB4/RB6	0.843	3.603	9.397	10.740	**0.491**
RB4/RB5	0.227	0.881	2.902	10.348	0.021
J1/RB5	0.206	0.762	1.741	12.407	0.026
B4/J1	0.227	2.806	1.034	16.388	0.026
J1/J2	0.108	4.413	1.503	15.060	0.023
J1/J3	0.122	2.880	1.216	10.184	0.035
J1/J5	0.136	3.103	1.481	13.168	**0.153**

The observed deltas of morphologic variables used in the MRPP analysis for Jeffers Creek show good clustering for bankfull depth measurements, with observed deltas of < 1 in all cases. Similar to Richland and Dry Creeks, measurements of bankfull width, bankfull width-to-depth ratio, and bankfull cross-sectional area in Jeffers Creek exhibited poor clustering having observed deltas > 1 in all but one case.

The similarity of channel shapes indicated by the MRPP analysis between B1/B3, B3/B4, RB4/RB1, RB4/RB2, RB4/RB3, RB4/RB6, and J1/J5 produces a spatial pattern of channel morphologic continuity in Jeffers Creek that largely spans the entire watershed (Figure 5.3). The spatial pattern of channel morphologic continuity encompasses the main channel of Jeffers Creek (indicated by study reaches with a prefix of J) and its two major tributary streams, Browns Creek (prefix of B) and Rice Branch Creek (prefix of RB).

Discussion

Overall patterns of continuity in channel morphology suggest spatial variability in sediment connectivity. Because of the significant role of sediment load in determining channel form, stream segments that exhibit reach continuity can be assumed to have a high degree of sediment connectivity or exchange, while stream segments lacking morphological continuity can be interpreted as having poor sediment connectivity.

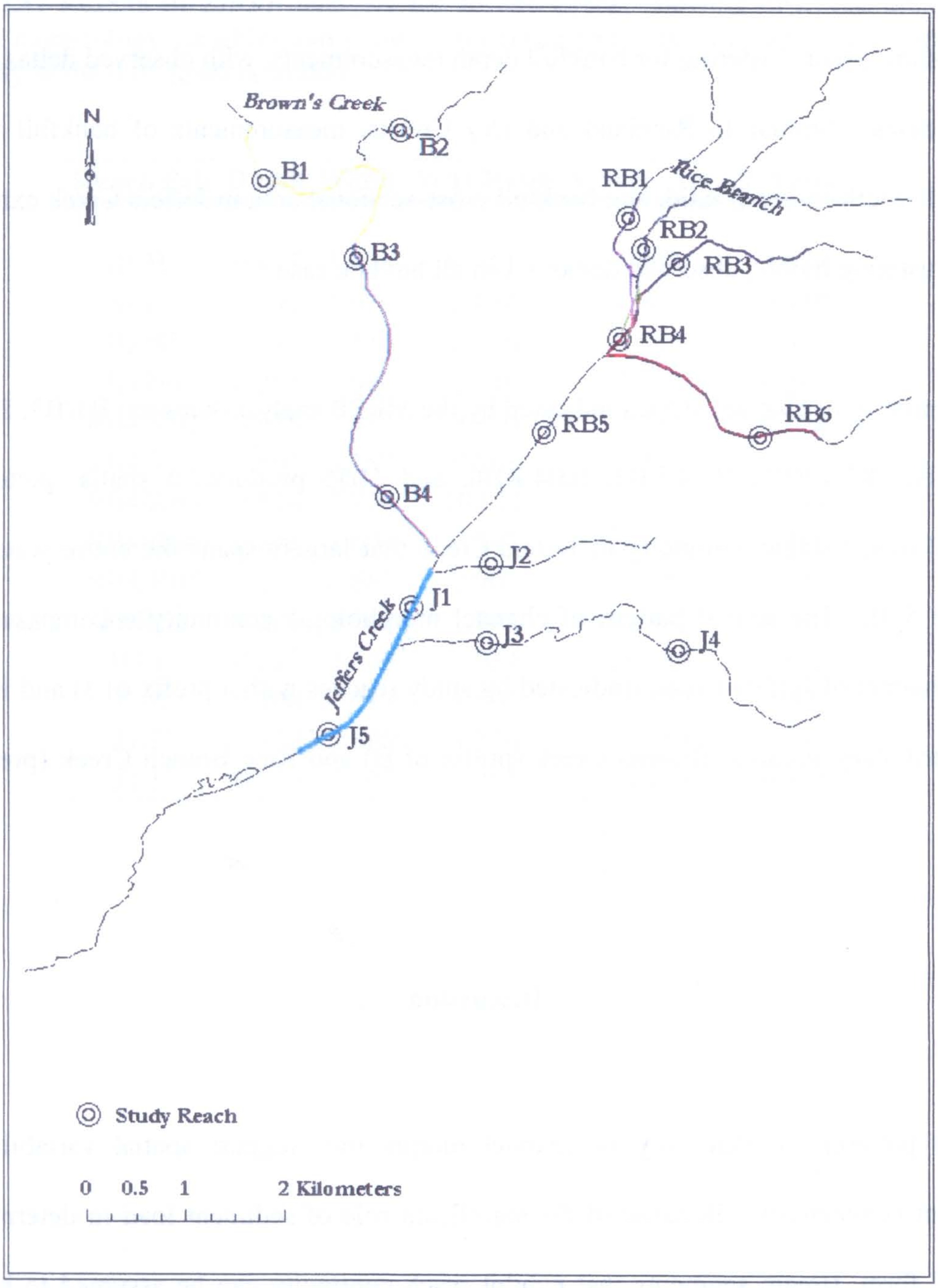

Figure 5.3: Spatial pattern of channel morphologic continuity in Jeffers Creek derived from MRPP analysis. Reaches mapped in the same color have similar channel shapes.

Poor sediment connectivity between some reaches within the same stream segment suggests a failure to transmit sediment from upstream. Potential explanations for this failure include: 1) the introduction of new sediment from local sources, and 2) the initiation of sediment storage. These two processes are probably not mutually exclusive.

The most likely local source of sediment is bank failure. All three of the study streams experience bank failure related to bank undercutting and over-steepening, either as a direct consequence of channelization (through ditching in channelized segments) or as an indirect consequence of channelization (base level adjustment in response to channelization in a downstream segment). Reaches with bank failure, especially large or catastrophic failures, already have a local sediment source from the addition of sediment from bank failures. The addition of sediment from upstream either overwhelms or further overwhelms the reach, exceeding the transport capacity of the reach and initiating storage. If this state persists, then the reach can experience net aggradation and the decrease in slope associated with prolonged net aggradation further decreases the transport capacity of the reach.

Reaches with continuity in channel morphology would be expected to also have a high degree of sediment connectivity, with upstream reaches serving as sediment sources to their adjacent downstream partners. Jeffers Creek, which exhibited the most reach continuity in channel shape, is the only one of the three study streams with an active and growing sediment blockage located at its mouth. The blockage is positioned downstream of study reach J5. The location of a sediment blockage at the mouth of Jeffers Creek supports the idea that channel morphologic continuity between adjacent reaches is indicative of a high degree of sediment exchange or sediment connectivity between reaches. A large amount of material is required to form a sediment blockage. It is reasonable to assume that not all of the sediment is derived locally. In addition, the results of the particle size analysis presented in Chapter 4 suggested that Jeffers Creek has the most consistency in particle size of the three study tributaries, which also supports there being a high degree of sediment connectivity in Jeffers Creek.

This study of sediment connectivity relied heavily on bankfull parameters. Other researchers have noted the difficulties associated with measuring bankfull indicators, such as discriminating between vegetation changes related to inundation frequency from vegetation changes related to bankfull discharge (Juracek and Fitzpatrick, 2003). Therefore, it is important to acknowledge the difficulties in recognizing bankfull stage in the field because of the possibility for inaccuracy. A consistently applied protocol does not exist for determining bankfull discharge in the field. I followed guidelines suggested by the United States Forest Service (Bunte and Abte, 2001), using field indicators such as the location of the active floodplain within the entrenched channel and the location of notches in exposed banks assumed to have formed during undercutting by bankfull flows. I did not rely on vegetation indicators, as vegetation is quick to re-establish in the Southeastern U.S. because of the humid, temperate climate. As a result, vegetation indicators can be misleading. Bank material throughout all the study watersheds is unconsolidated, making it highly erodible. For this reason, the bankfull channel morphology I observed and measured in the field may actually represent typical bankfull morphology for the basins studied or could very well only represent changes in channel morphology as a consequence of the most recent storm event, bankfull or otherwise. However, I made every effort to be consistent with my evaluation of bankfull stage in the field. The observed delta values for bankfull depth derived from the MRPP analysis provide evidence that my field determination of bankfull was consistent throughout the streams. The observed deltas suggested a high degree of clustering of bankfull depth measurements in each study tributary with observed delta values of < 1 in every instance.

Conclusions

Results of this study suggests that some stream segments within the study tributaries have better sediment connectivity than others, as indicated by similar channel shapes. Connections between different components of the fluvial system do not always operate in a linear manner. Previous studies of sediment dynamics discussed in Chapters 3 and 4 suggested that sediment transport in the study tributaries is irregular due to limited availability of consistent or adequate discharge. Results from this study of sediment connectivity seem to support the proposition that sediment transfer is irregular throughout each system. Channel morphologic continuity was not consistent throughout any one tributary. But Jeffers Creek did exhibit some evidence of system-wide sediment connectivity.

The use of MRPP and channel morphology measurements to approximate sediment transfer between reaches has potential to provide insight into spatial patterns of geomorphic processes. This technique may be most effective as a first step towards choosing field sites to monitor reach-scale sediment dynamics.

The inconsistent nature of sediment transport in the study tributaries emphasizes the need to understand the spatial and temporal variability of sediment processes and to be able to identify the relative importance of reach-scale processes versus watershed-scale processes in adjusting, tributary streams.

CHAPTER 6

Conclusions

Spatio-Temporal Patterns of Geomorphic Adjustment

This dissertation research was undertaken to study issues of geomorphic adjustment in channelized, tributary streams. Broad issues addressed by this dissertation include: 1) identifying geomorphic processes active in the tributaries, 2) examining the connections between sediment dynamics and geomorphic adjustment processes, and 3) examining the applicability of an existing conceptual model of geomorphic adjustment post-channelization in tributary streams with multiple episodes of disturbance. Results of this dissertation indicate that processes of channel widening and sediment dynamics, particularly at the reach-scale, are heavily involved in geomorphic adjustment to channelization in tributary streams of the Lower Hatchie River (LHR). Figure 6.1 provides a conceptual framework of the ways that reach-scale processes, such as sediment storage and bank failure, may translate into system-wide geomorphic adjustment based this study of geomorphic adjustment in the study tributaries.

The study tributaries located in the LHR are still adjusting to channelization that occurred over 30 years ago. Analysis of channel morphology, bank failure processes, and particle

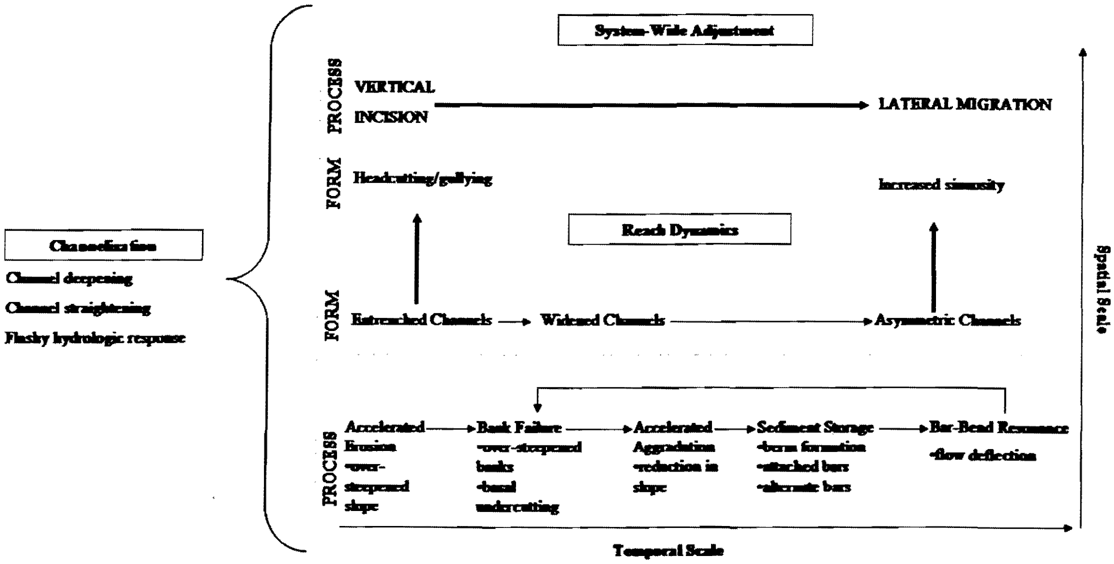

Figure 6.1: Connections between reach and system–scale geomorphic dynamics operating in alluvial, tributary streams of the LHR.

size analysis throughout the three tributaries indicates that the dominant geomorphic adjustment process operating throughout the tributaries is channel widening produced by the deflection of flow around sediment stored in the channel in the form of bars and berms.

Evidence of channel widening and sediment storage processes found in channel morphology measurements, bank process observations, and sediment monitoring in Richland Creek all suggest that bar-bend processes may be part of lateral adjustment processes active in the tributaries. The possibility of bar-bend processes being active in widening channels of the study tributaries is an important observation, as the cause of lateral migration processes in alluvial rivers remains heavily debated. It suggests that sediment storage in the channel is an important determining factor in initiating increased channel sinuosity and continuing channel widening processes. Sediment monitoring conducted over a seven-month period in one study tributary, Richland Creek, suggests that bank erosion processes are progressive and that sediment berms and bars formed in the channel have life spans of at least several months, giving additional support to the operation of bar-bend processes in widening reaches. This dissertation research is among only a few field-based studies to find evidence of bar-bend lateral migration processes in operation, and one of the first to highlight the potential role of bar-bend processes in geomorphic adjustment to channelization in tributary, alluvial streams. Application of an existing conceptual model of geomorphic adjustment in channelized streams, the Channel Evolution Model (Simon, 1994), in the LHR tributary streams identified limitations of such models. The CEM emphasizes vertical adjustment processes. In light of the connections between channel widening processes of adjustment and sediment dynamics, especially sediment storage, identified by this dissertation research, there is a significant need for conceptual models of adjustment to include lateral migration processes, specifically as a result of sediment storage. In addition, the CEM may have limited application in streams in which the location of the area of maximum disturbance is not known or includes multiple locations because not all stages of adjustment may occur or be identifiable. The limitations of the CEM highlighted as a result of this research have important implications for state and federal natural resource agencies and non-governmental organizations involved in watershed restoration and management, which may use the CEM for monitoring and making management decisions.

Results of this dissertation also suggest that sediment dynamics may require a significant amount of time to adjust to channelization, which may cause changes in other geomorphic adjustment processes. Results of the floodplain coring and ^{137}Cs dating of sediments from the only re-coupled floodplain in Richland Creek revealed that it has taken more than 50 years for this channel/floodplain re-coupling to occur and that has occurred relatively recently. Limited floodplain/channel re-coupling will result in continued storage of sediment in the channels as berms and bars, which may cause widening and aggrading processes to persist well into the future. Investigation of particle size changes in the study tributaries was not able to establish any evidence of hydraulic sorting of sediment. Analysis of channel morphology measurements as a proxy for sediment connectivity using the multi-response permutation procedure (MRPP) suggested limited sediment transferal in the study tributaries. A lack of hydraulic sorting of channel sediment and dissimilarity of channel shape in the tributary streams suggests poor sediment transfer between reaches, which may be related to the dominance of reach-scale sediment sources and a lack of consistent and/or adequate discharge to transport channel sediment that persists in the tributaries. The irregular transfer of sediment within the study tributaries identified in this study highlights the need to better understand the spatial and temporal variability of sediment processes and to be able to identify the relative importance of reach-scale processes versus watershed-scale processes in adjusting, tributary streams. Non-linear response of sediment dynamics has significant implications for the use of numerical models in the study of sediment dynamics in channelized, tributary streams. Non-linear response occurs in the study tributaries as a consequence of reach-scale sediment dynamics. However, most numerical models are designed to operate at the watershed scale, which may thus limit the abilities of such models to accurately represent sediment dynamics in alluvial, tributary streams adjusting to channelization.

Study Limitations and Subjects for Future Research

Several issues not included in this dissertation research are worthy of mention and perhaps future research. First, I did not interpret aerial photographs in this research.

Aerial photograph interpretation, especially using a time series of images, would be helpful in establishing the residence time of channel sediment in storage, such as berm deposits, and in establishing channel widening rates. Instead, I chose to monitor bank failure and berm development in the field at a few representative locations because I believed that rates of channel widening from bank failure and of berm development might have been underestimated if measured from aerial photography because the time between available sets of images was, at best, 20 years.

I did not study the occurrence and development of the sediment blockage located at the mouth of Jeffers Creek. Sediment blockages appear to develop over the course of decades and aerial photographic analysis would have been necessary to understand its formation. Because of the frequency of bank failures, coarse woody debris was present in many stream reaches and in the sediment blockage on Jeffers Creek. Although I did not include coarse woody debris in this study, it is likely to play a role in channel morphologic change by enhancing or instigating widening by flow deflection and/or enhancing or instigating deposition by acting as a sediment trap. Coarse woody debris, acting as a sediment trap, may also aid in the development of sediment blockages.

This research addresses spatial and temporal patterns of geomorphic adjustment processes. It was not possible to separate adjustment processes that occur as a consequence of historic land clearance and adjustment processes that occur as an indirect consequence of channelization. This issue arises with all studies of change in fluvial systems that occurred over periods of decades or longer because of the endurance of legacy effects in fluvial systems and because the current state of any given fluvial system is dependent on the entire history of that system up to and including the present day. My interpretation of one sediment core to examine the long-term depositional history of one of the study tributaries is a first step to understanding long-term sediment behavior in fluvial systems of this region. A more complete depositional history will be achieved when cores are taken and analyzed from multiple locations throughout the watersheds.

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